The future of the liquid argon technology in astroparticle physics

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AstroParticule et Cosmologie (APC)

Astroparticle Symposium

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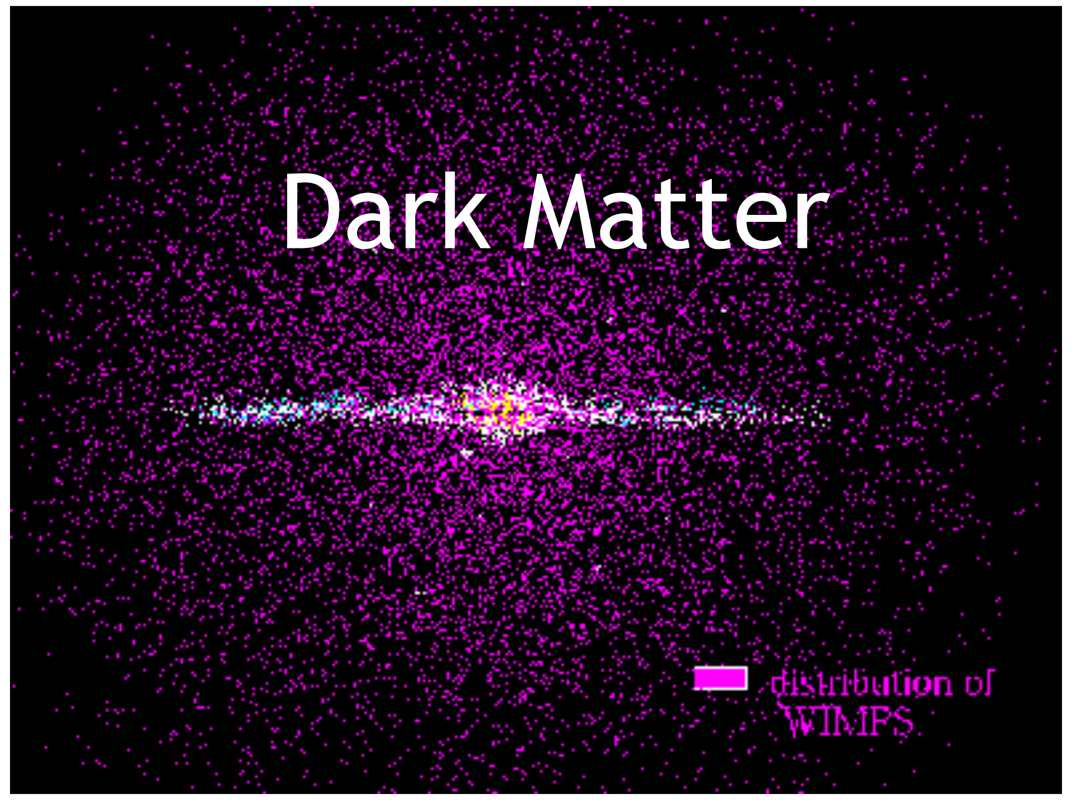
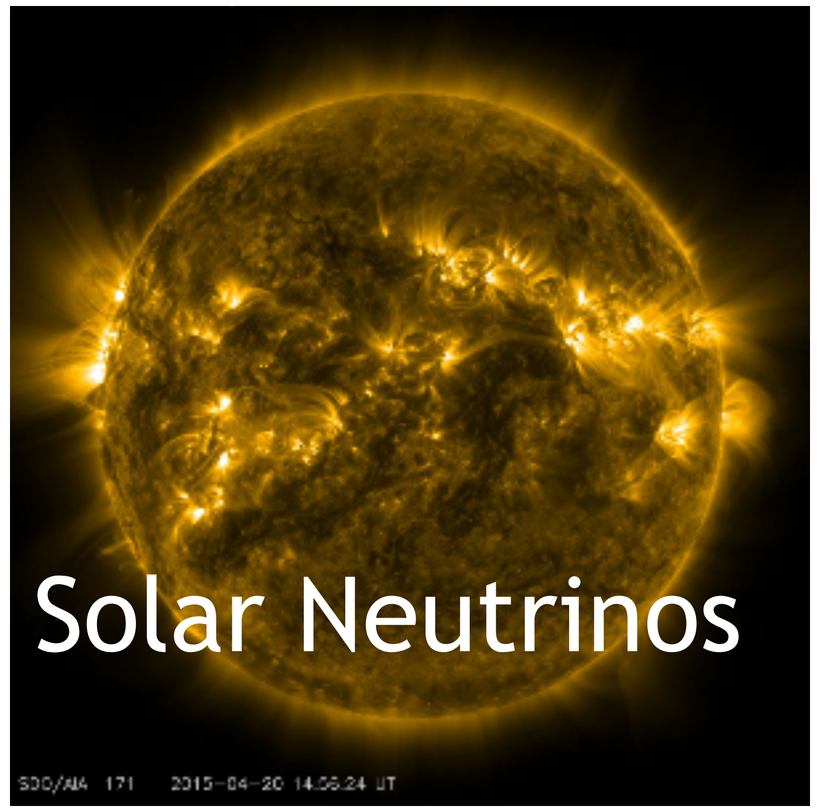
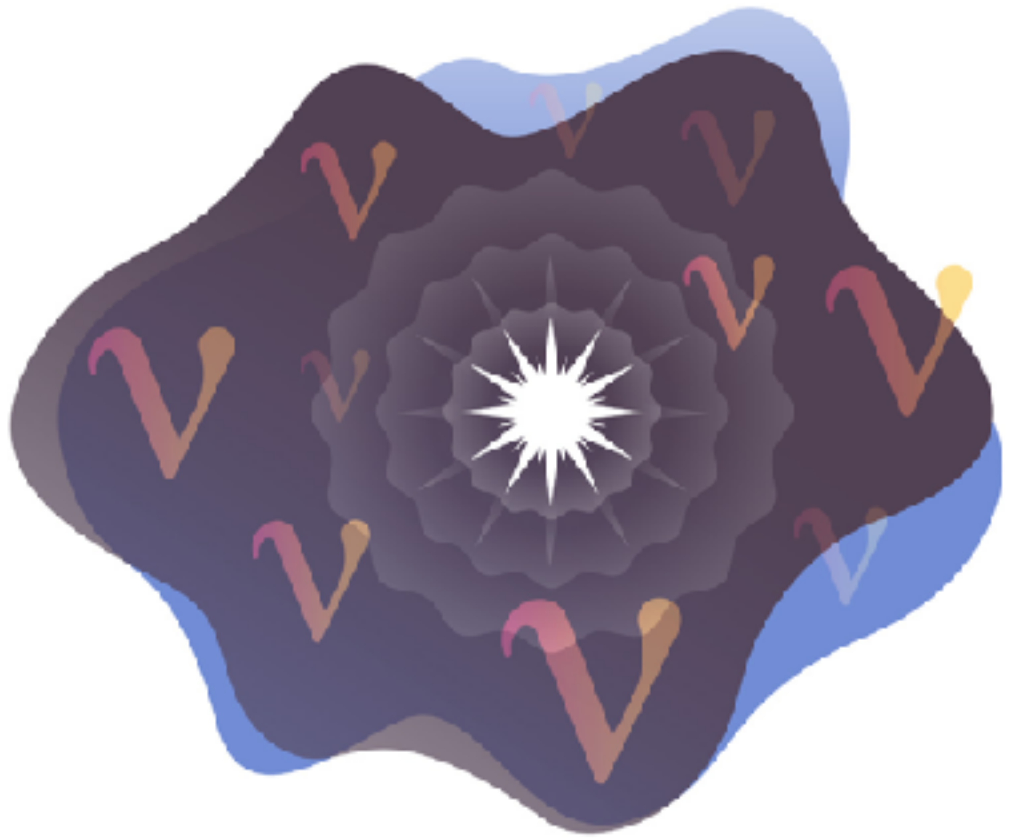
Liquid argon applications in astroparticle



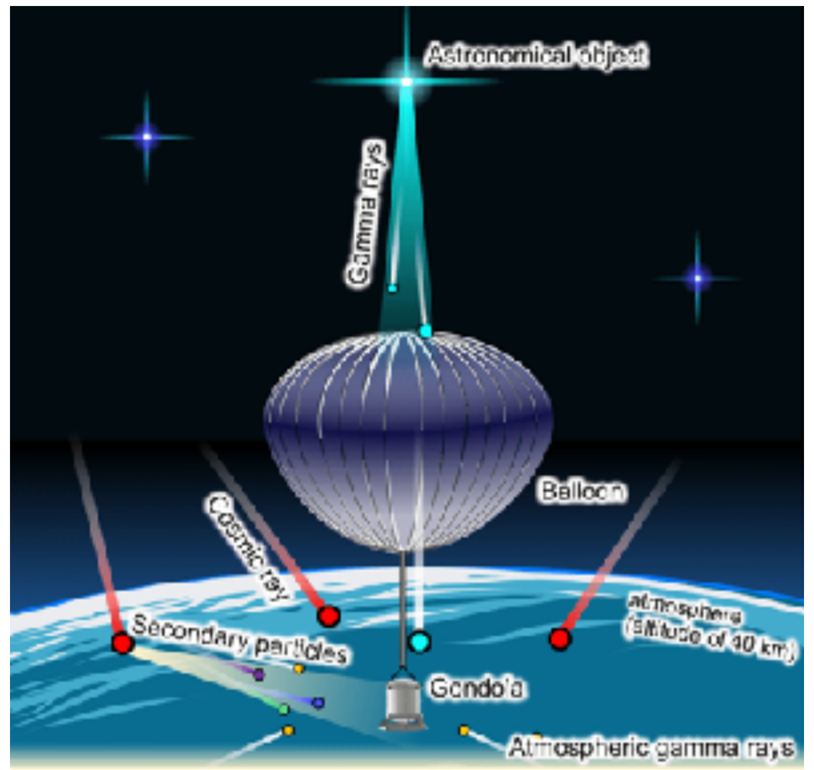


Accelerator Neutrinos

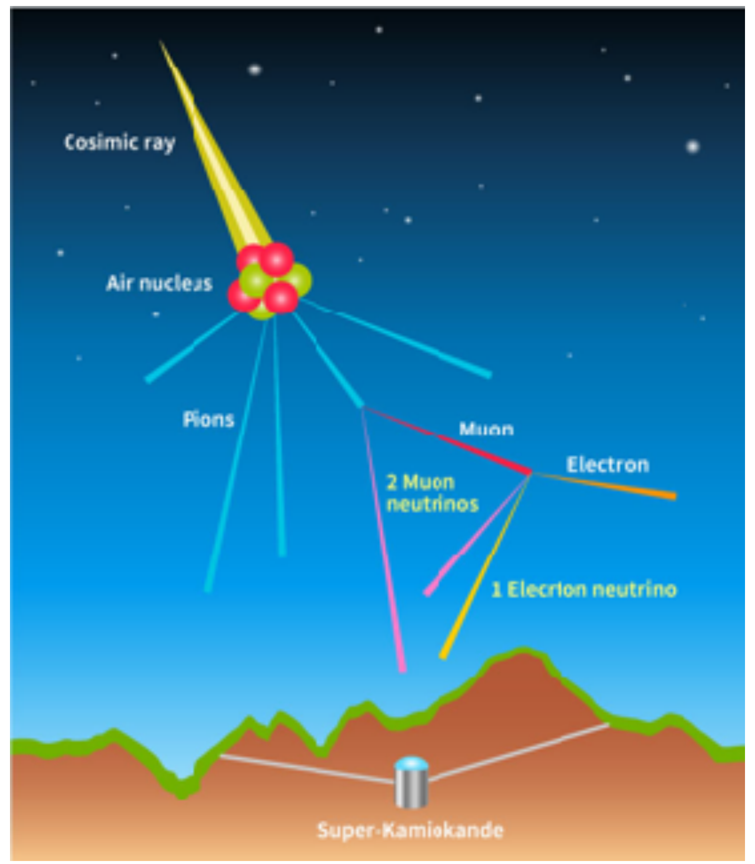
eV keV MeV GeV



Supernova neutrinos



Gamma ray astronomy

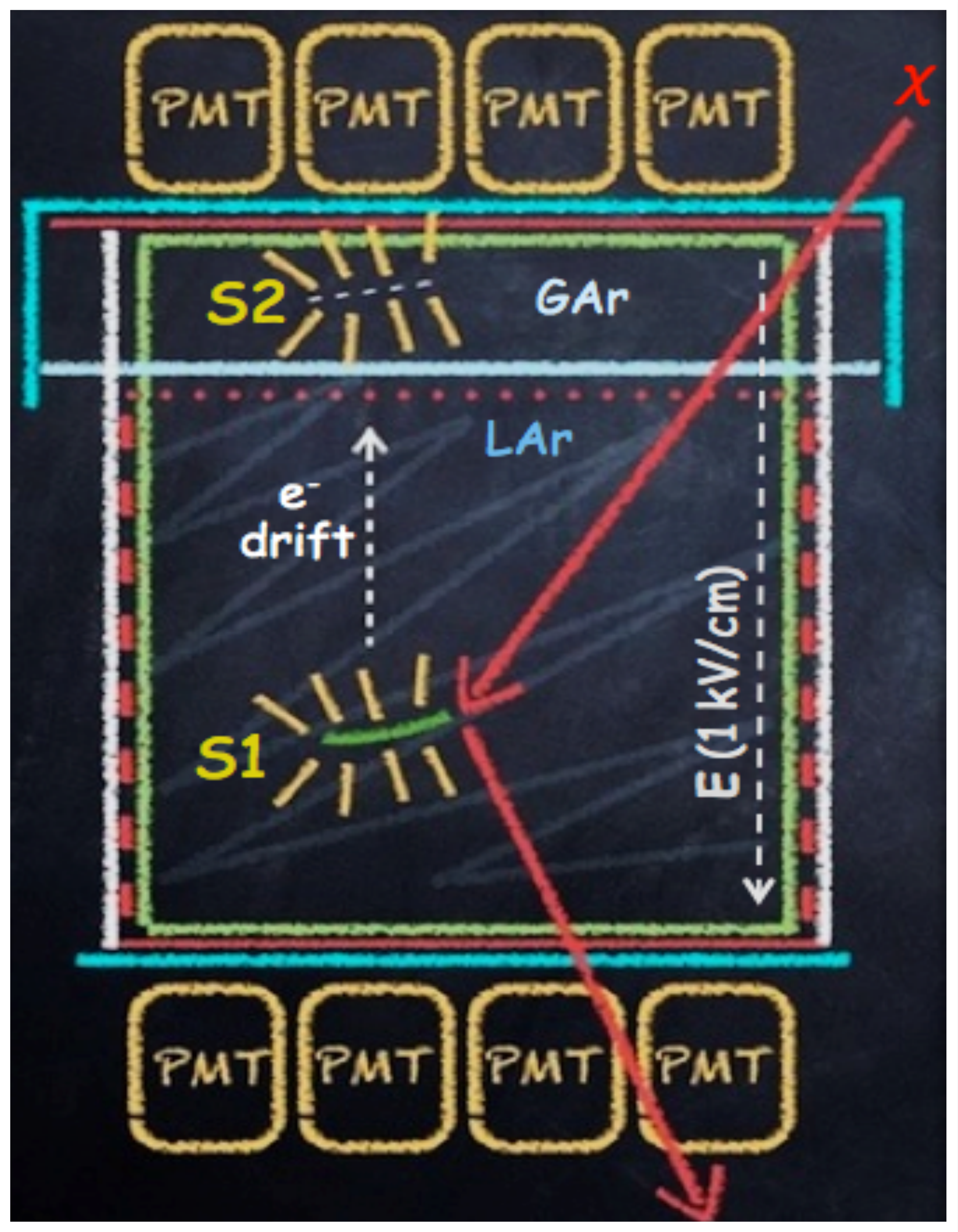


Atmospheric neutrinos

The astroparticle physics programme

Energy Range	Physics Target	Experiments
0.1 - 100 keV	Light Dark Matter + SN ν (CEνNS)	DarkSide, ARGO
30 - 500 keV	High-mass WIMP Dark Matter	DarkSide, DEAP-3600, ARGO
0.6 - 14 MeV	Solar Neutrinos (ES)	ARGO
1 - 10 MeV	Gamma-ray astronomy	GammaTPC, eGRAMS
5 - 15 MeV	Solar Neutrinos (CC)	DUNE
5 - 50 MeV	Supernova ν (CC on ^{40}Ar)	DUNE
10 - 250 MeV	ν from DM annihilation (π^+/K^+ DAR)	DarkSide, DUNE, ARGO
1 - 5 GeV	Accelerator neutrinos	MicroBooNE, ICARUS, DUNE
1- 10 GeV	Atmospheric ν / mass ordering	DUNE

Dominant technology: Time Projection Chamber



Simultaneous detection of scintillation and ionization

Dual-phase:
- Electrons extracted to gas phase
- Charge readout: proportional scintillation (S2) or segmented anode in gas
- Light readout: SiPMs
- Examples: DarkSide, WA105

Single-phase - Horizontal Drift (HD):
- Electrons drift horizontally in liquid
- Charge readout: wire planes
- Light readout: SiPMs integrated in APAs
- Examples: DUNE-HD, ProtoDUNE-HD

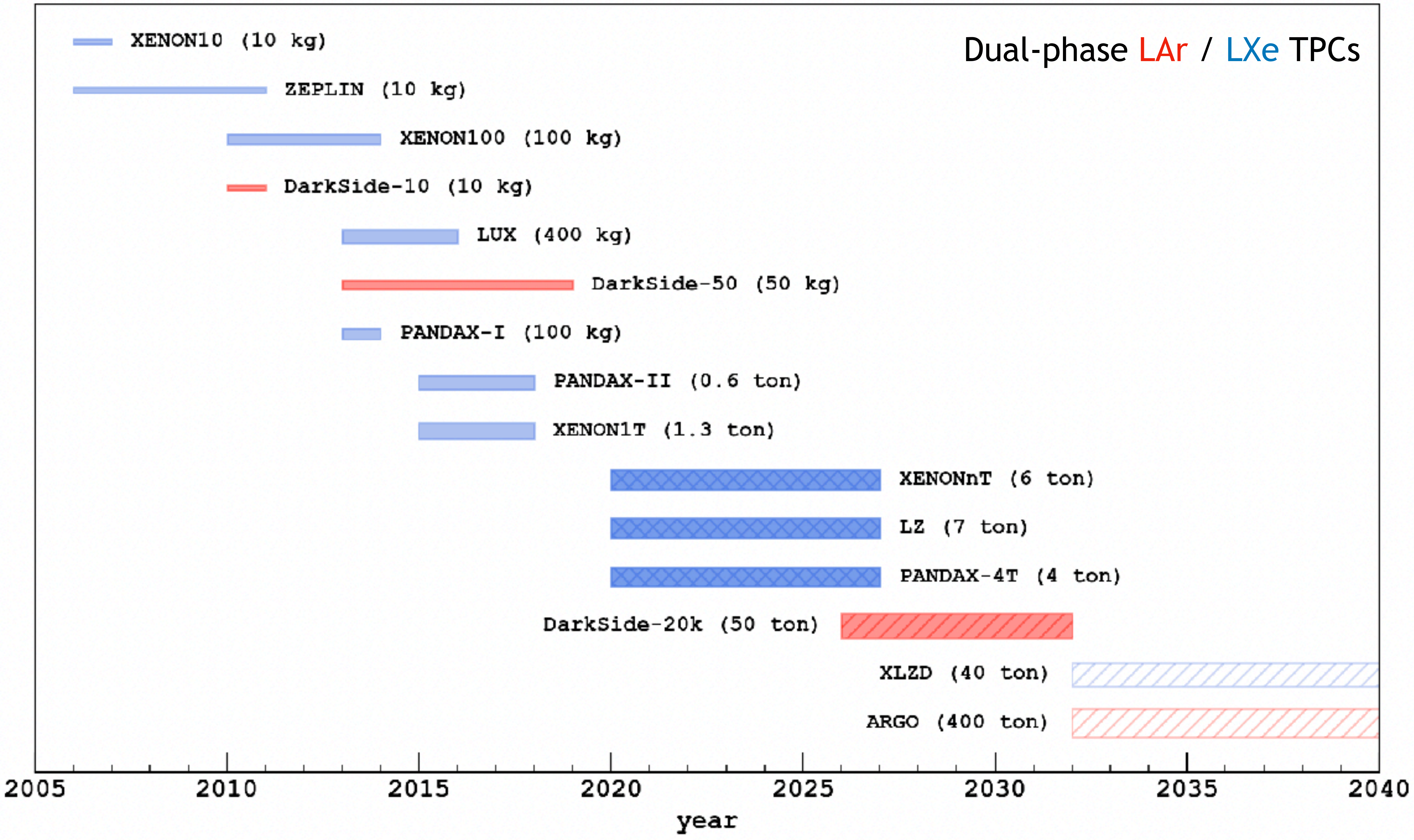
Single-phase - Vertical Drift (VD):
- Electrons drift vertically in liquid
- Charge readout: segmented anode plane
- Light readout: SiPM
- Examples: DUNE-VD

Particle discrimination through:
Accurate 3D position identification
Multiple-scattering rejection
S2/S1 ratio
Pulse Shape Discrimination

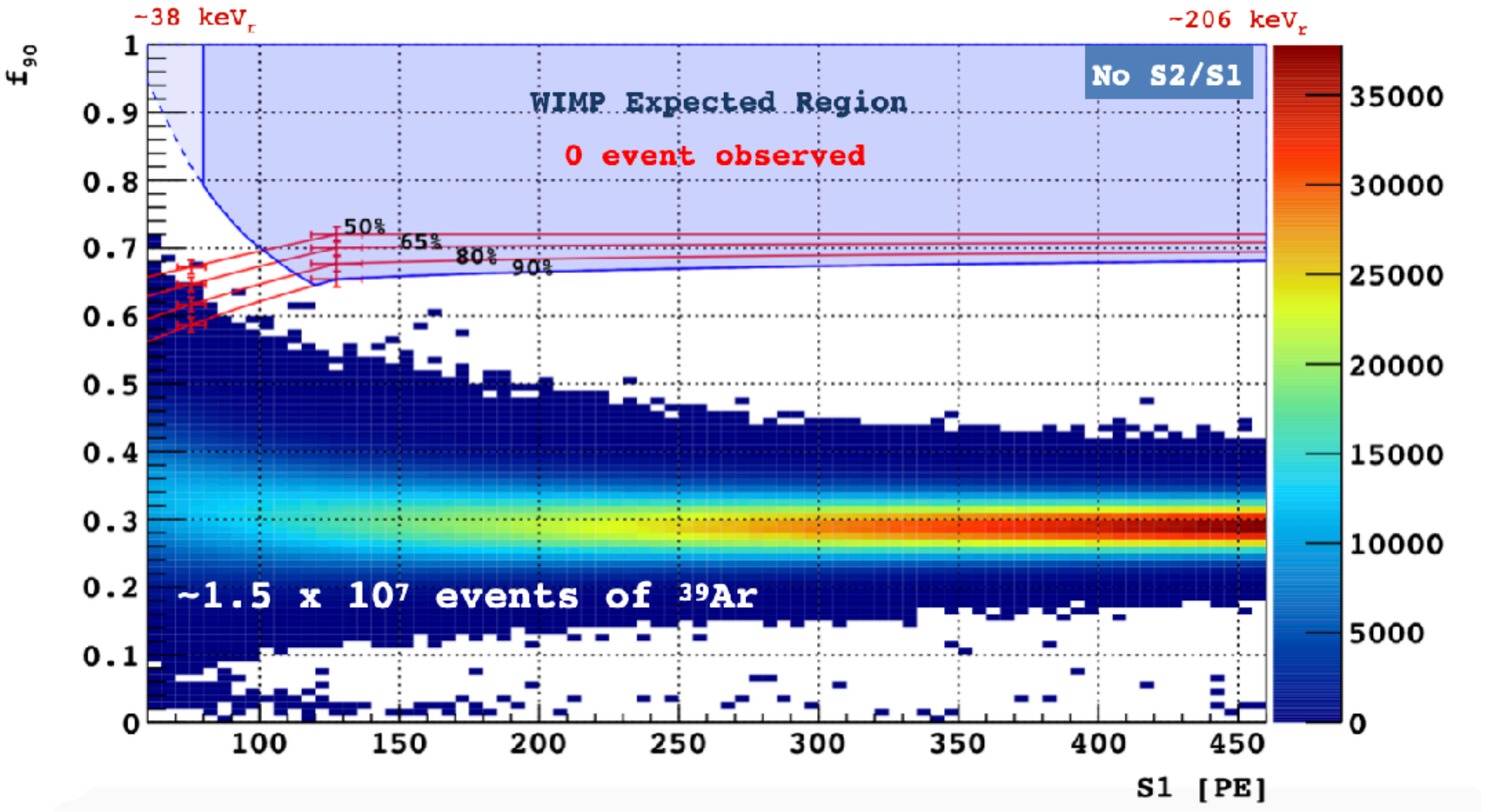
Dual-Phase Noble Liquid TPCs for Dark Matter Search

Noble Liquids

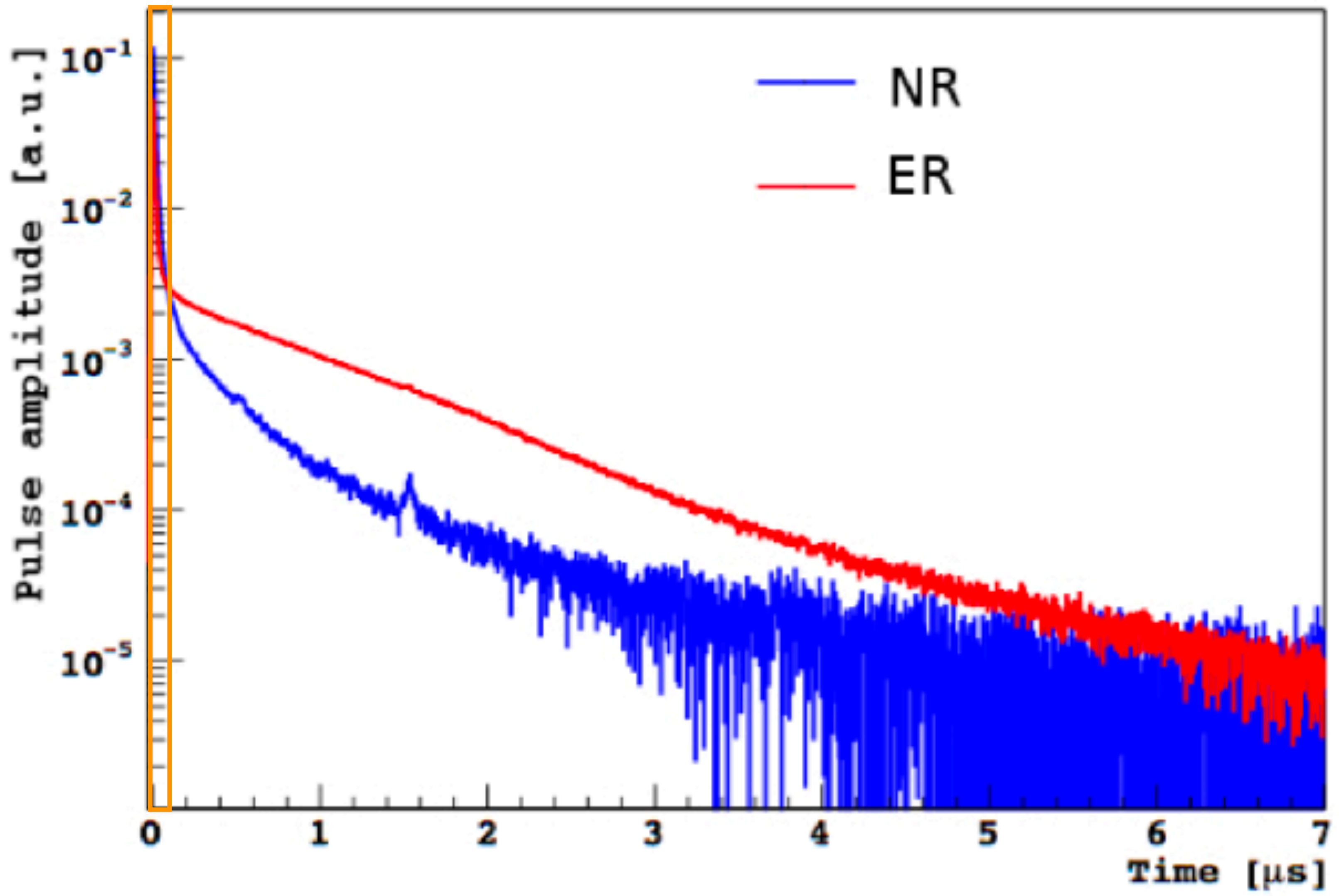
- **Noble**
  => no radiochemical impurities
- **Scalable**
  => O(10-100 ton)
- High **scintillation** yield (x 4 organic scintillator)
  => high resolution
- Excellent particle **identification**
  => background suppression
- High **ionization** yield
  => very low energy thresholds
- Low electron **diffusion** and mobility
  => accurate event topology in a TPC



The Scintillation Pulse Shape Discrimination



f90: fraction of detected light in the first 90 ns

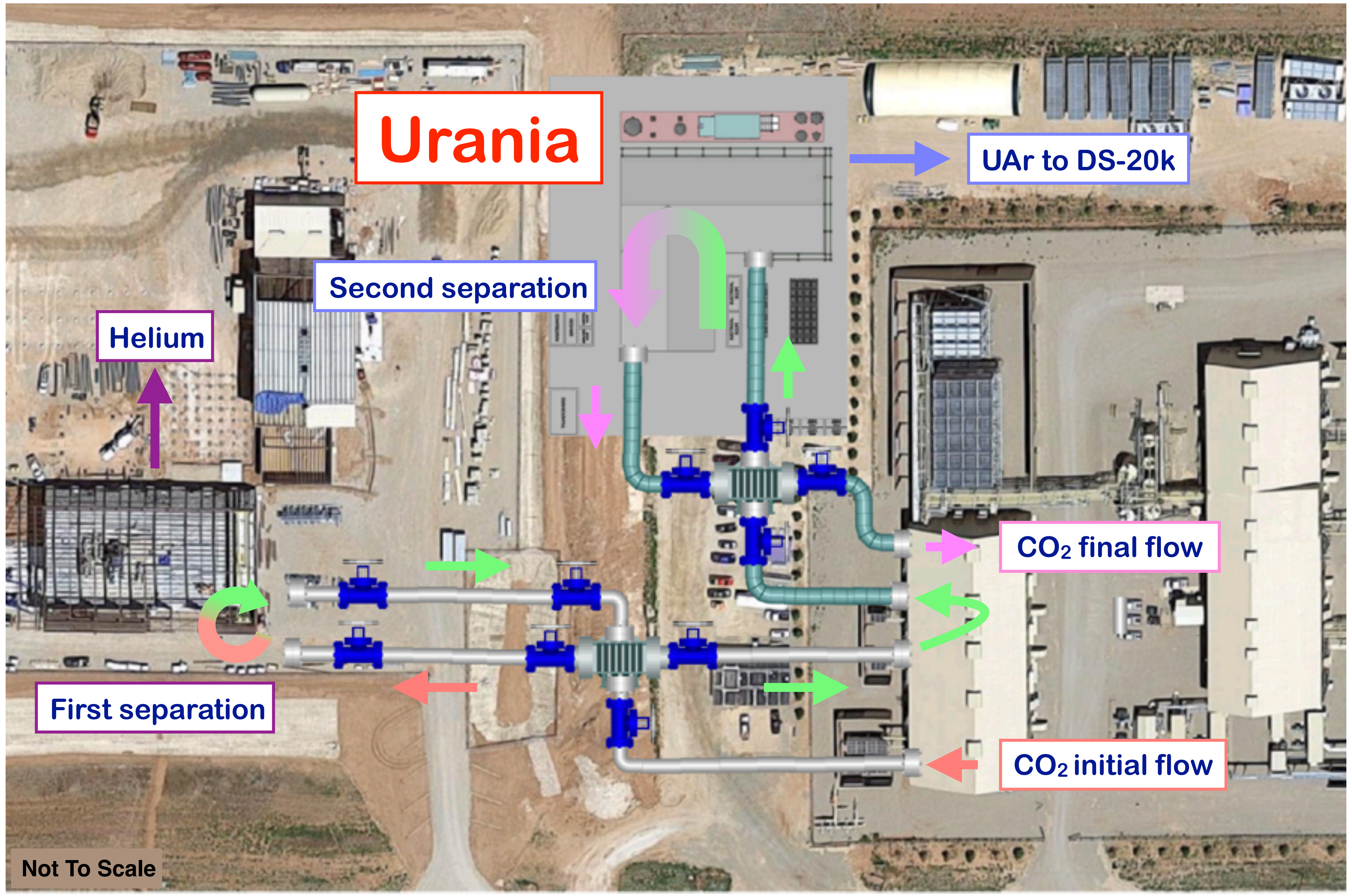


Potential for a **background-free** multi-ton experiment

Extraction with Urania

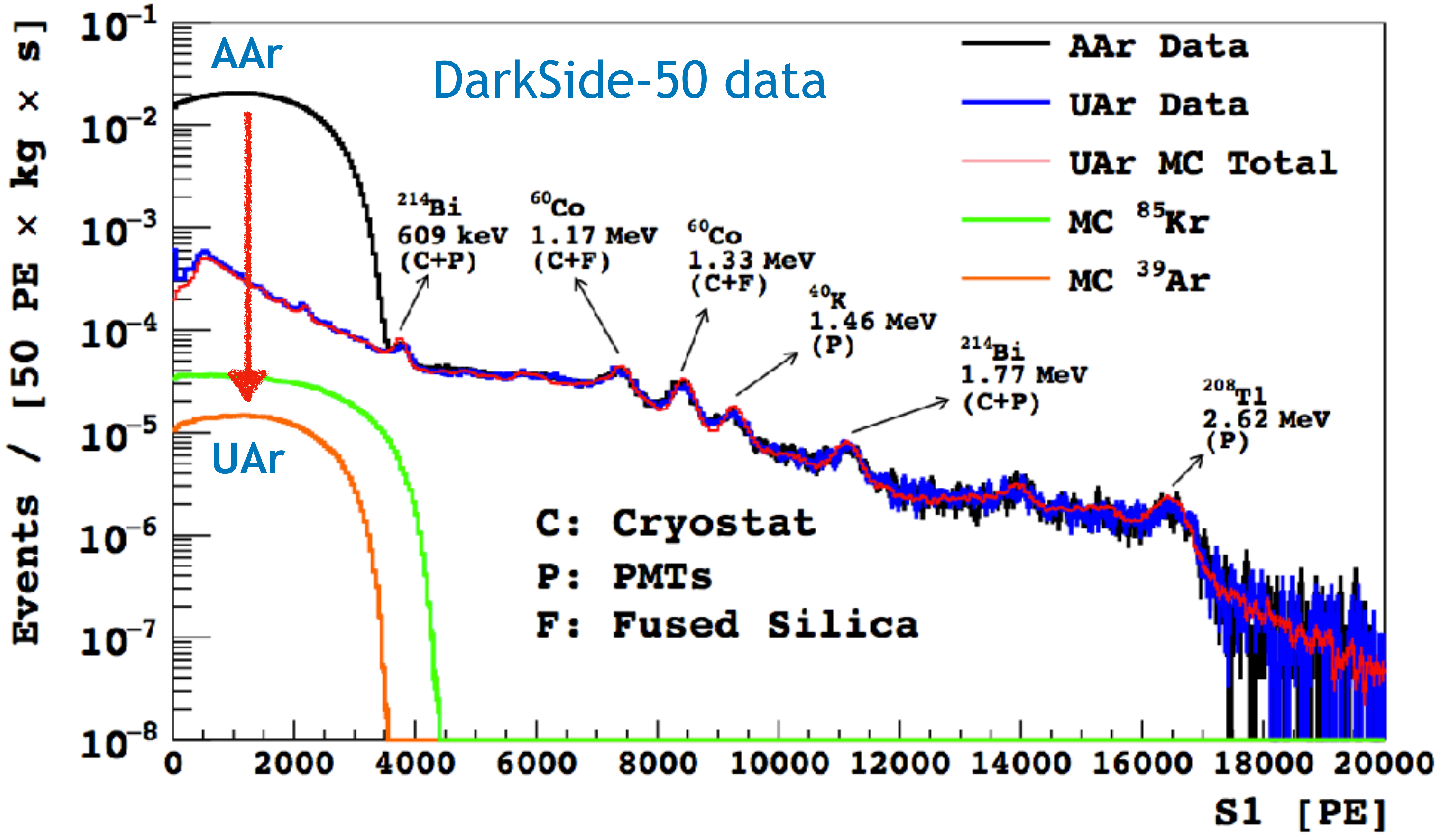
Expansion of the industrial scale plant in Cortez, to reach capacity of **250 kg/day** of Underground Argon

Initial purity: 99.99%



Why ~~not~~ liquid argon?

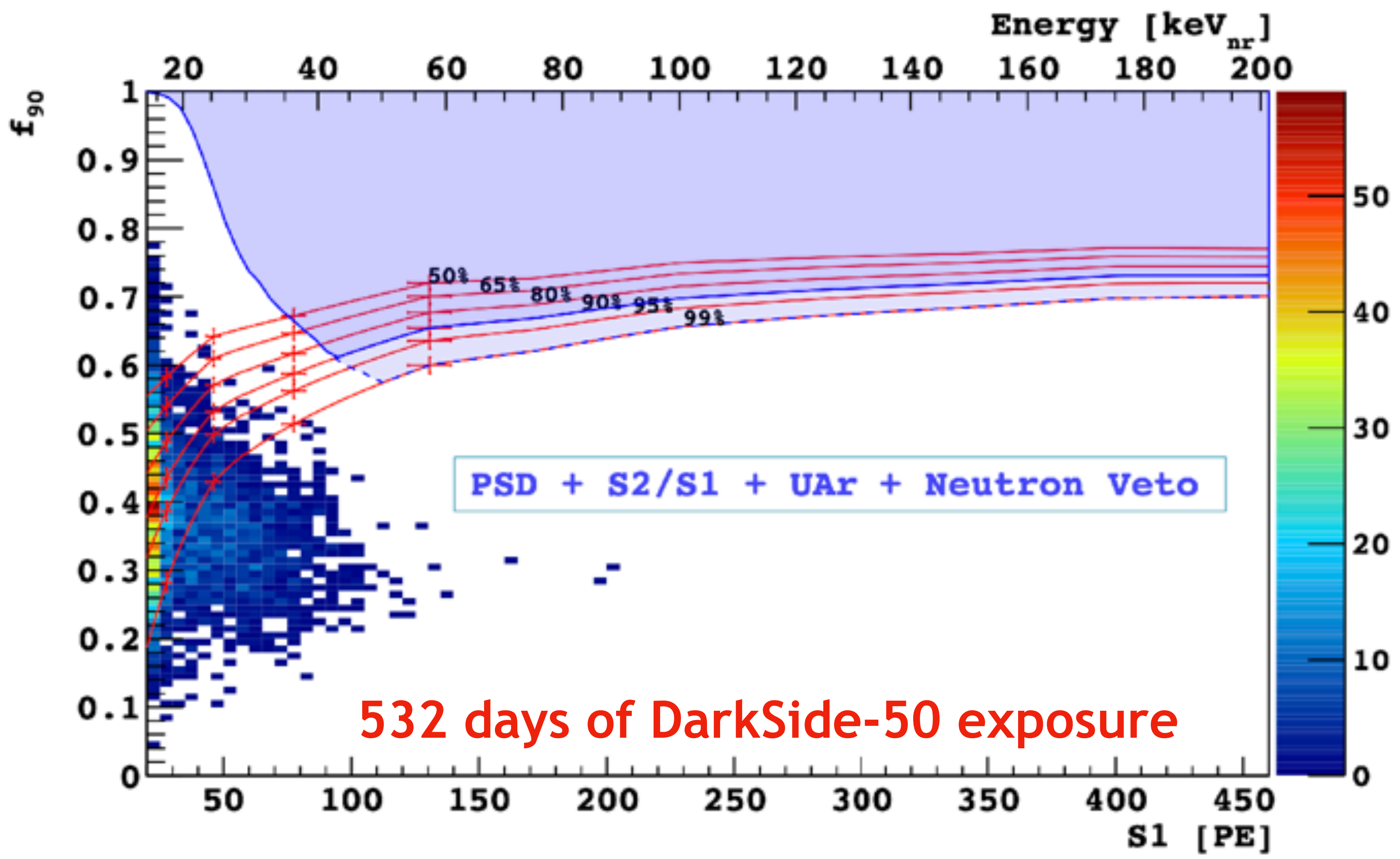
Underground Argon



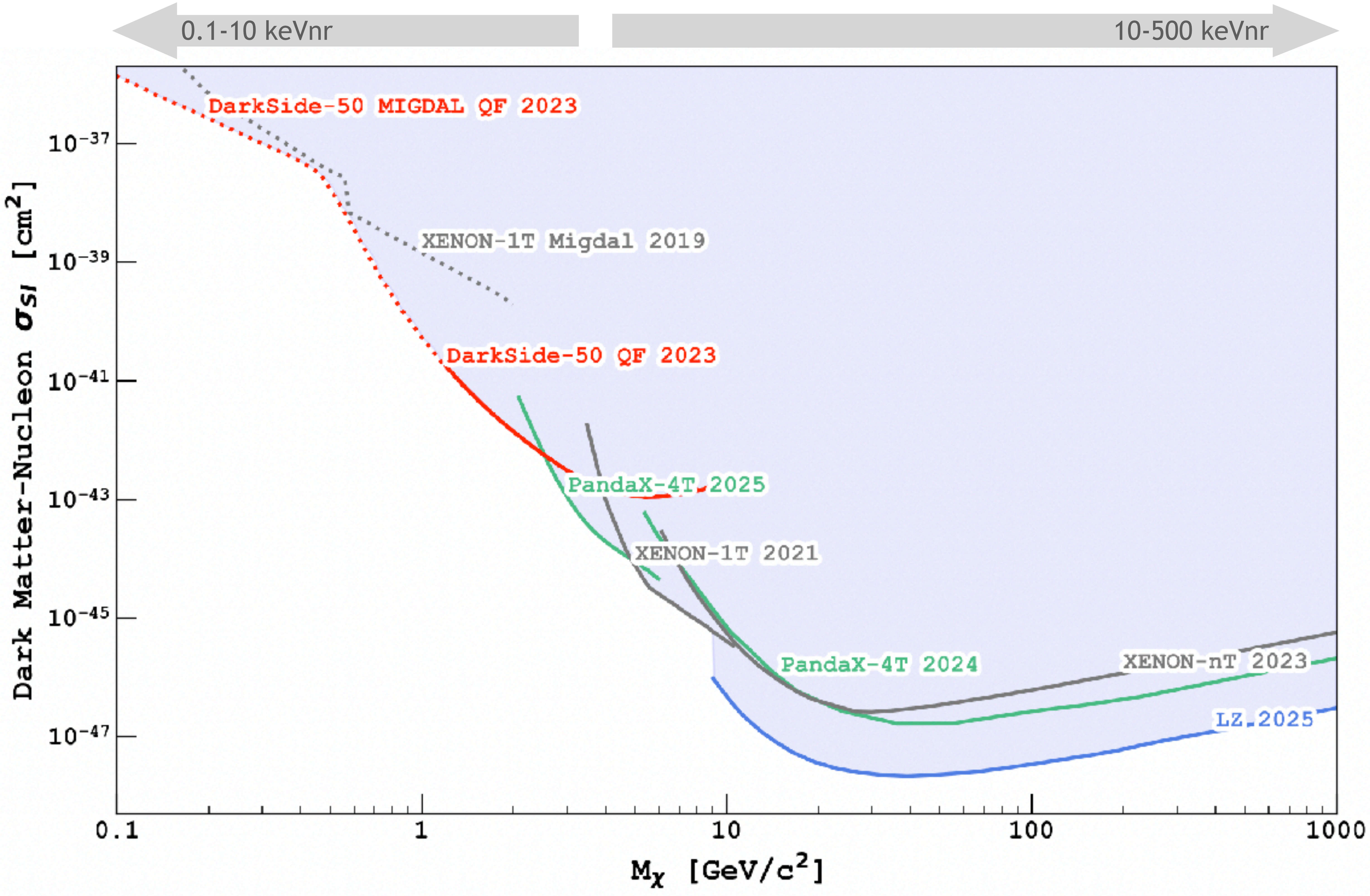
^{39}Ar reduction factor in UAr: ~1400

Cosmogenic ^{39}Ar in **atmospheric argon** is the primary background (~1 Bq / kg)

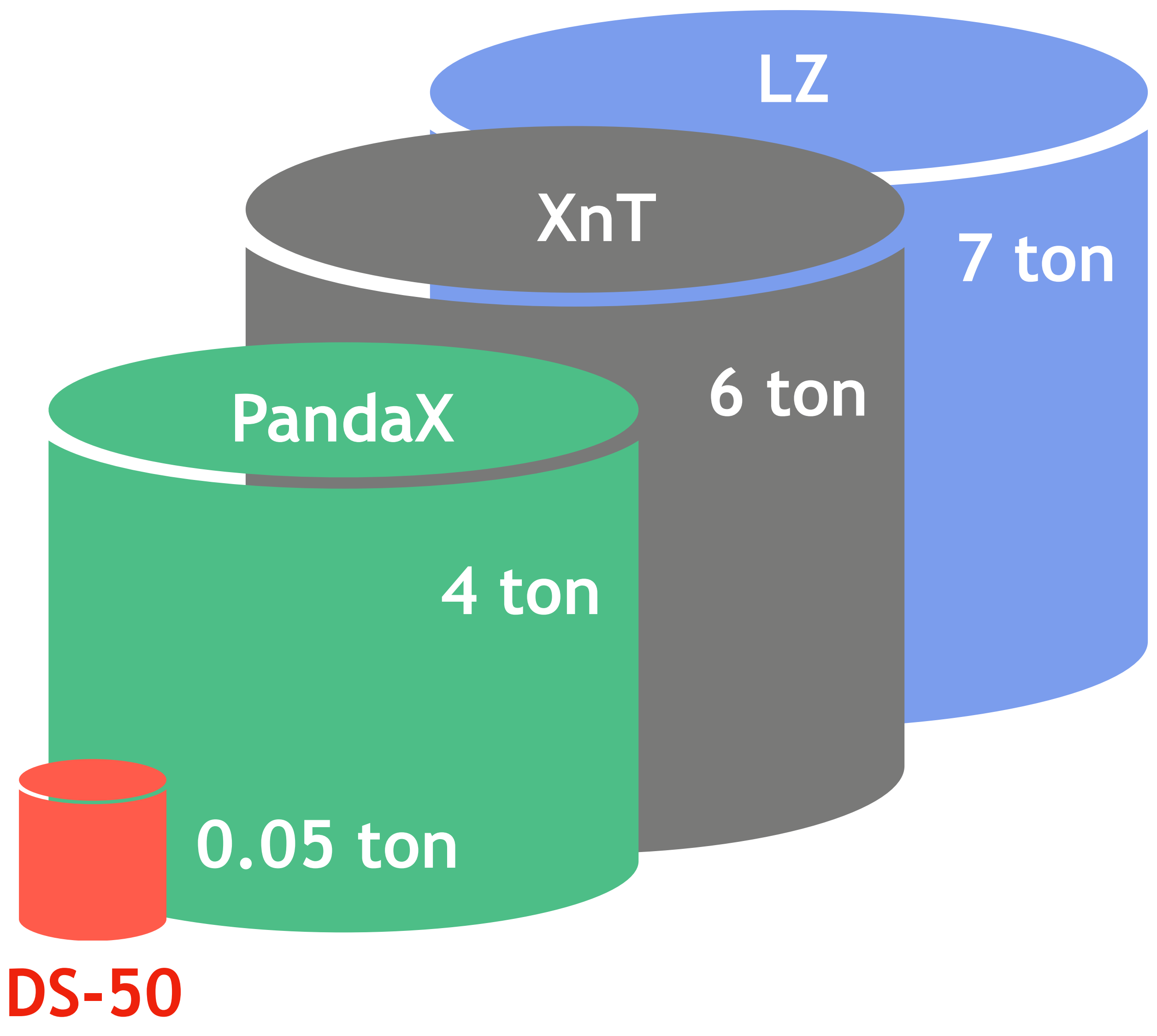
Argon extracted from deep underground is naturally shielded against cosmic rays



Current limits on DM-Nucleon SI interactions



- **Dual-phase TPCs** dominate WIMP searches from the sub-GeV scale
- **DarkSide-50**, with only 50 kg of LAr, **competitive** with respect to multi-ton LXe detectors.

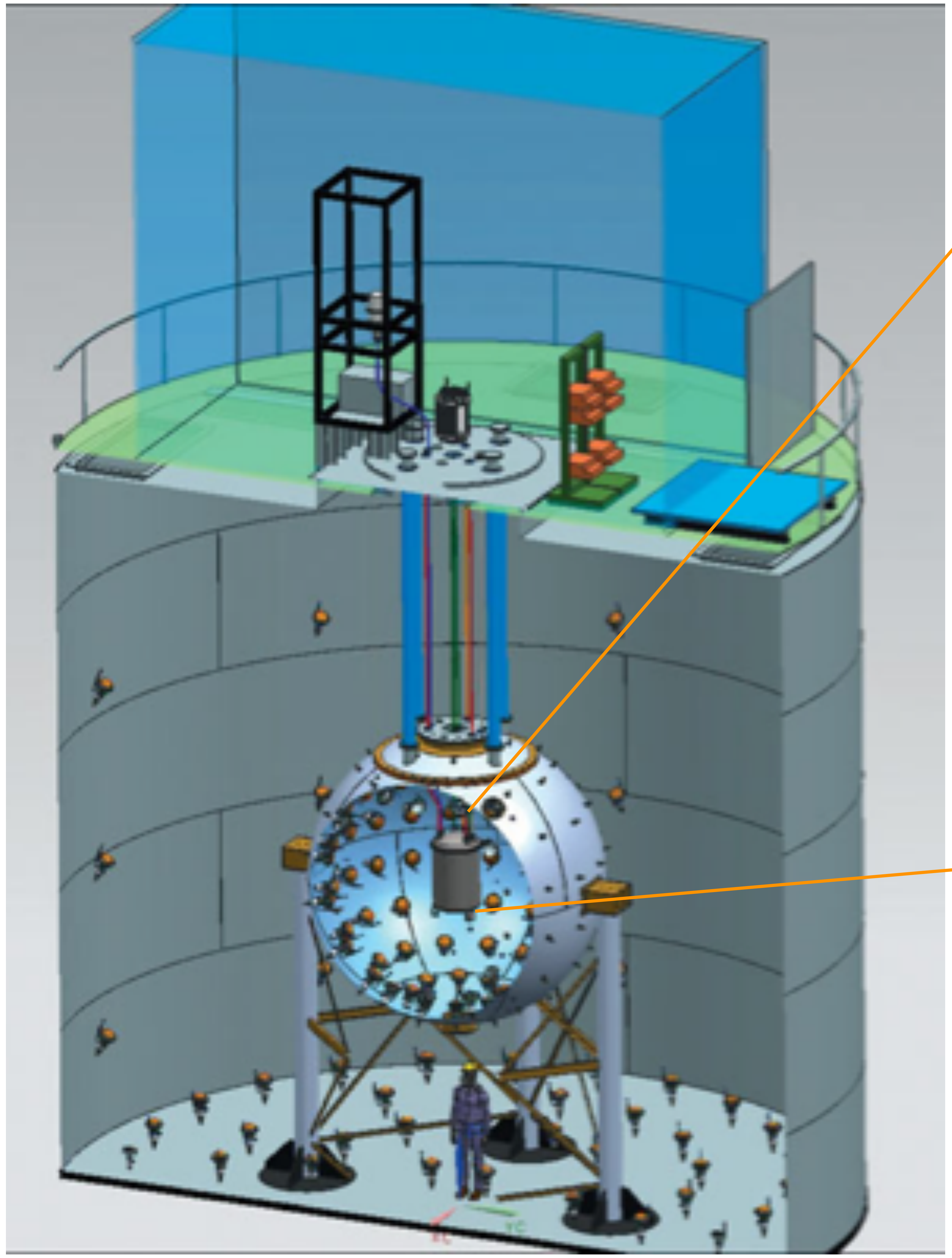


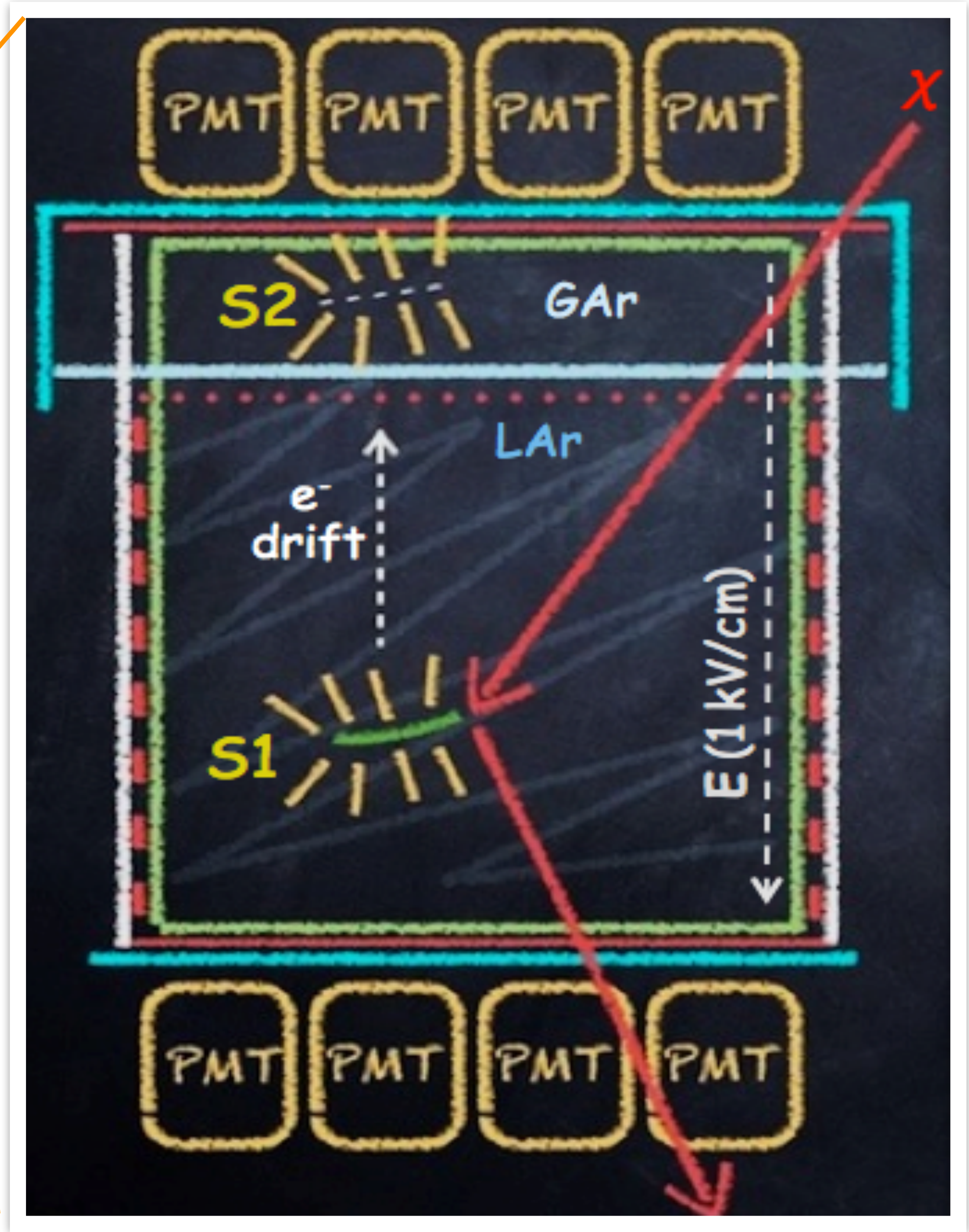
DS-50: so sensitive despite its size…

The Dual-Phase TPC
- 50 kg active mass of UAr
- 19 top + 19 bottom R11065 HQE 3’’ PMTs
- 36 cm height, 36 cm diameter
- Low field of 0.2 kV/cm drift

Liquid Scintillator Veto against neutrons
- 4 m diameter sphere
- Boron-loaded: 1:1 PC and TMB
- 110 8” PMTs
- LY ~ 500 pe/MeV

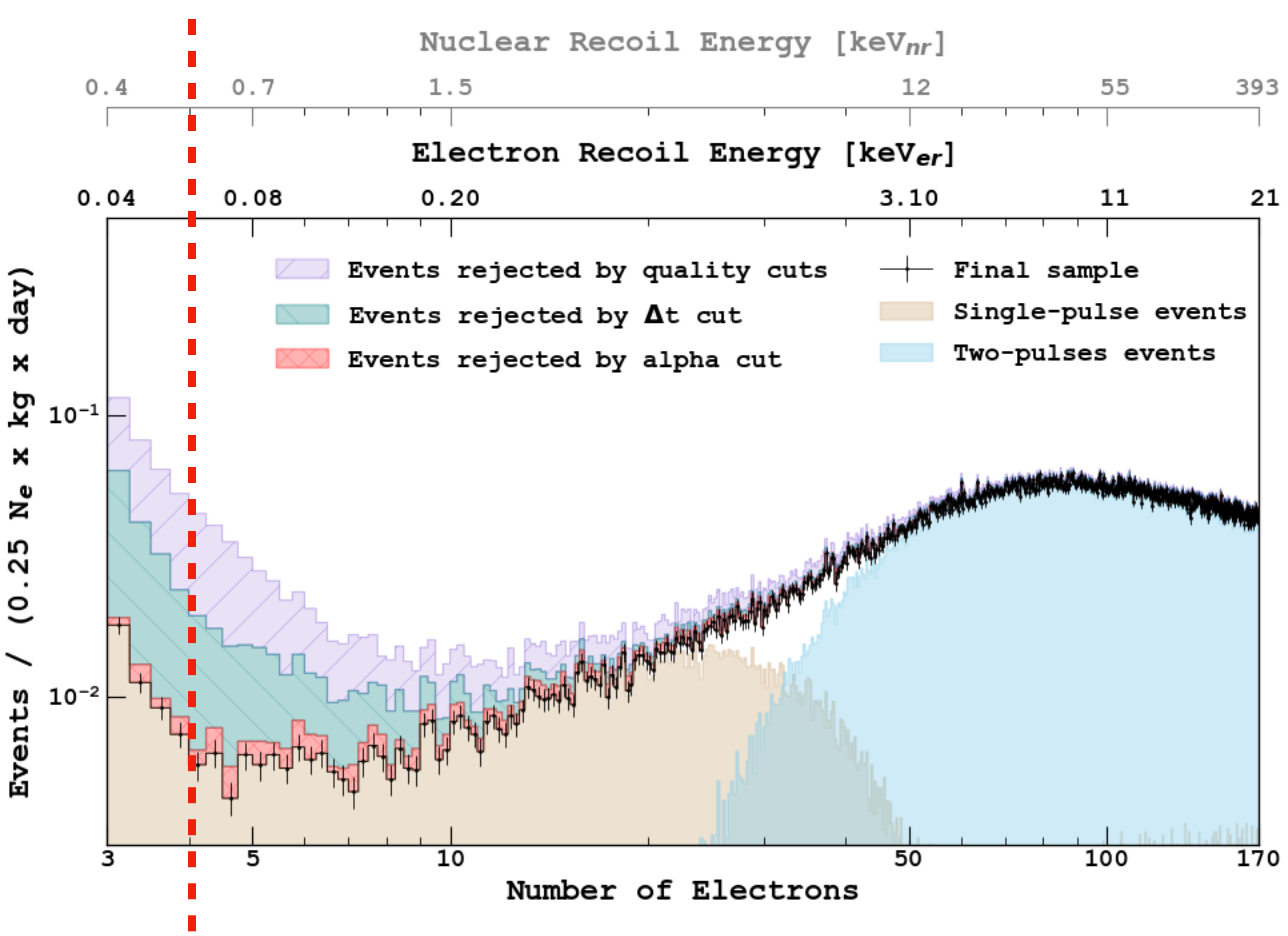
Cherenkov Water Detector
- 11 m diam. x 10 m
- 80 PMTs





Low-Mass Analysis

Dropping scintillation (16% detection efficiency) —> 100% detection efficiency of S2 at 2 e-



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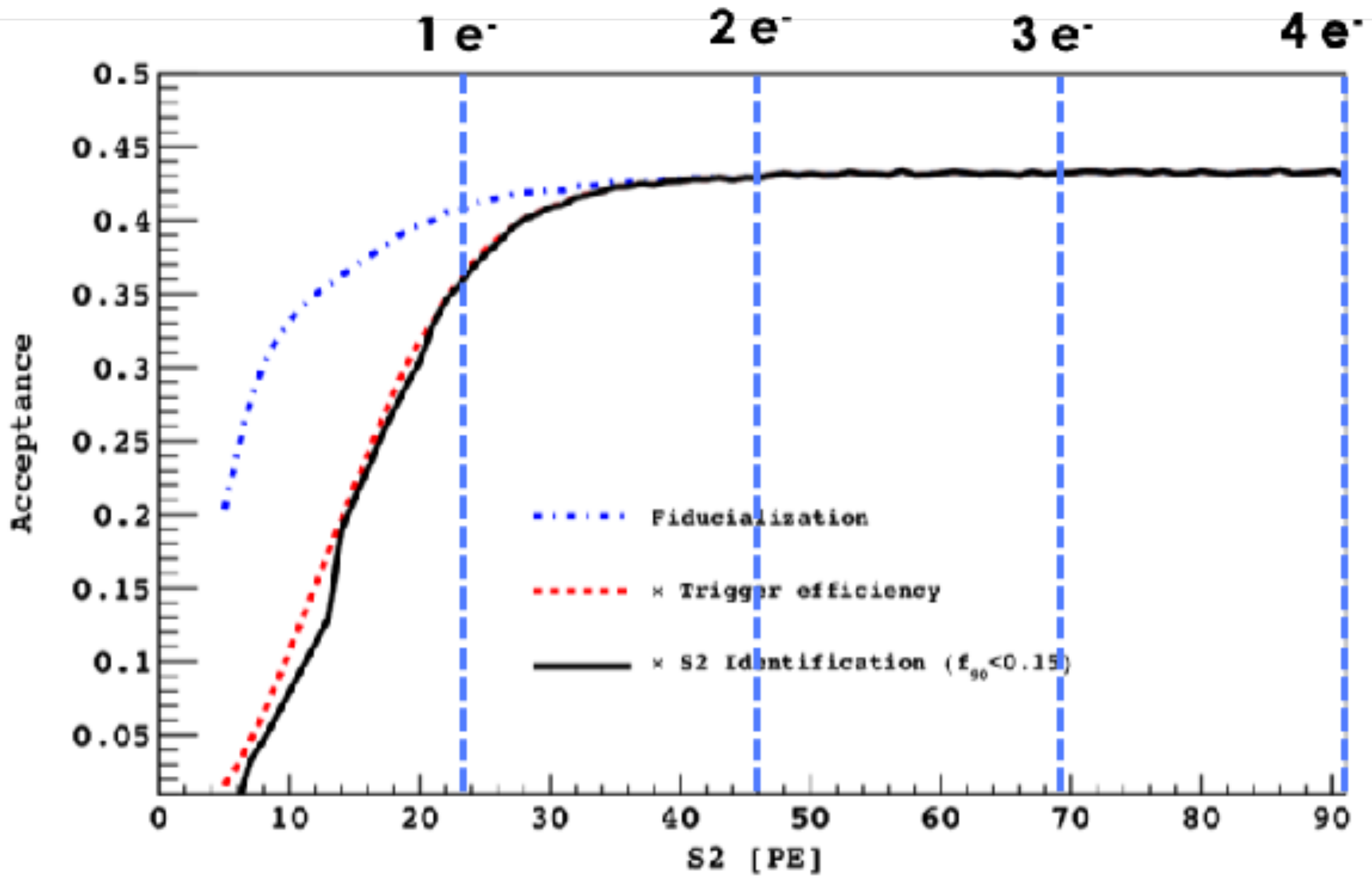


Exposure

- 650 live-days or 12 ton-day

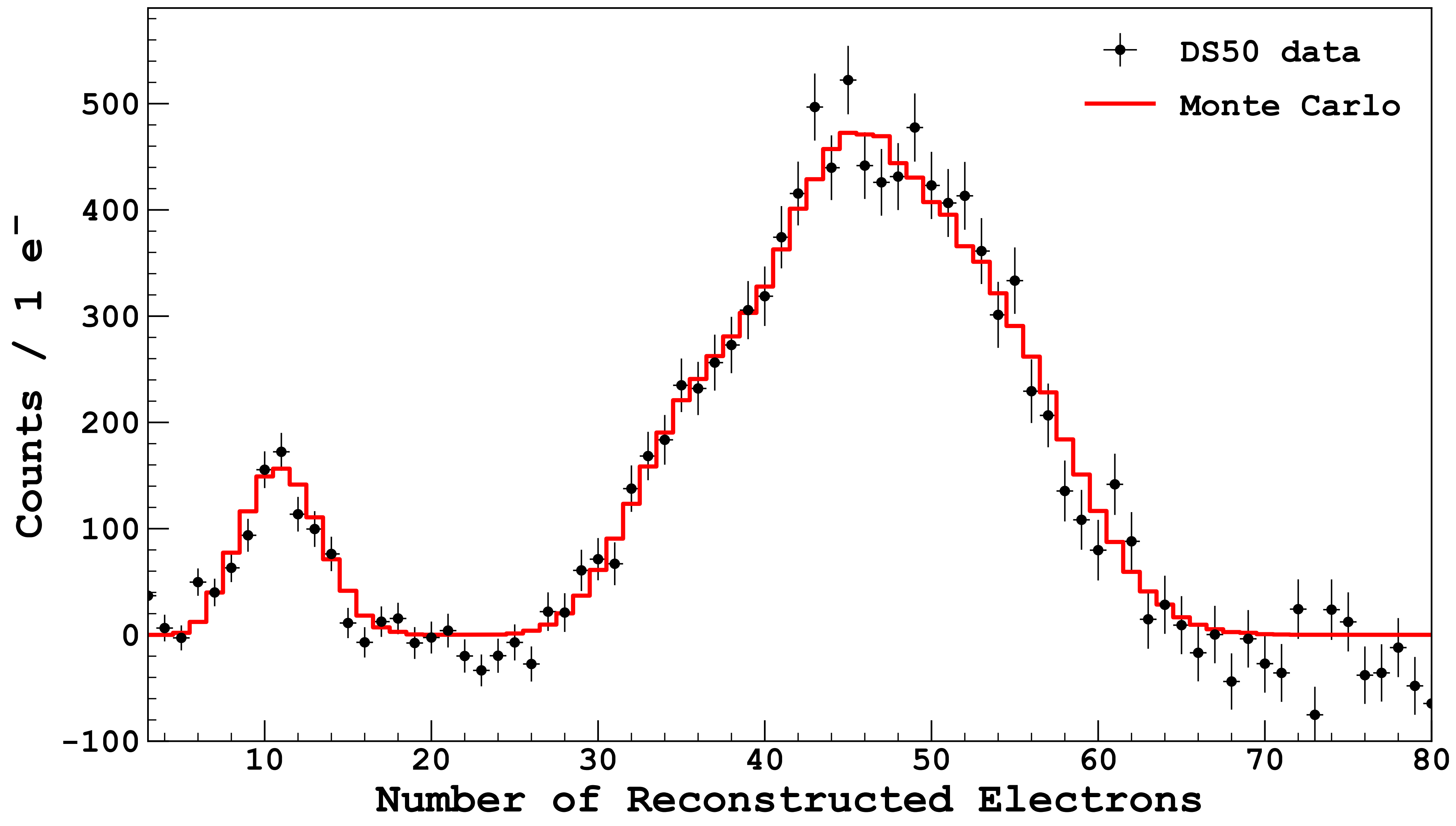
Data Selection

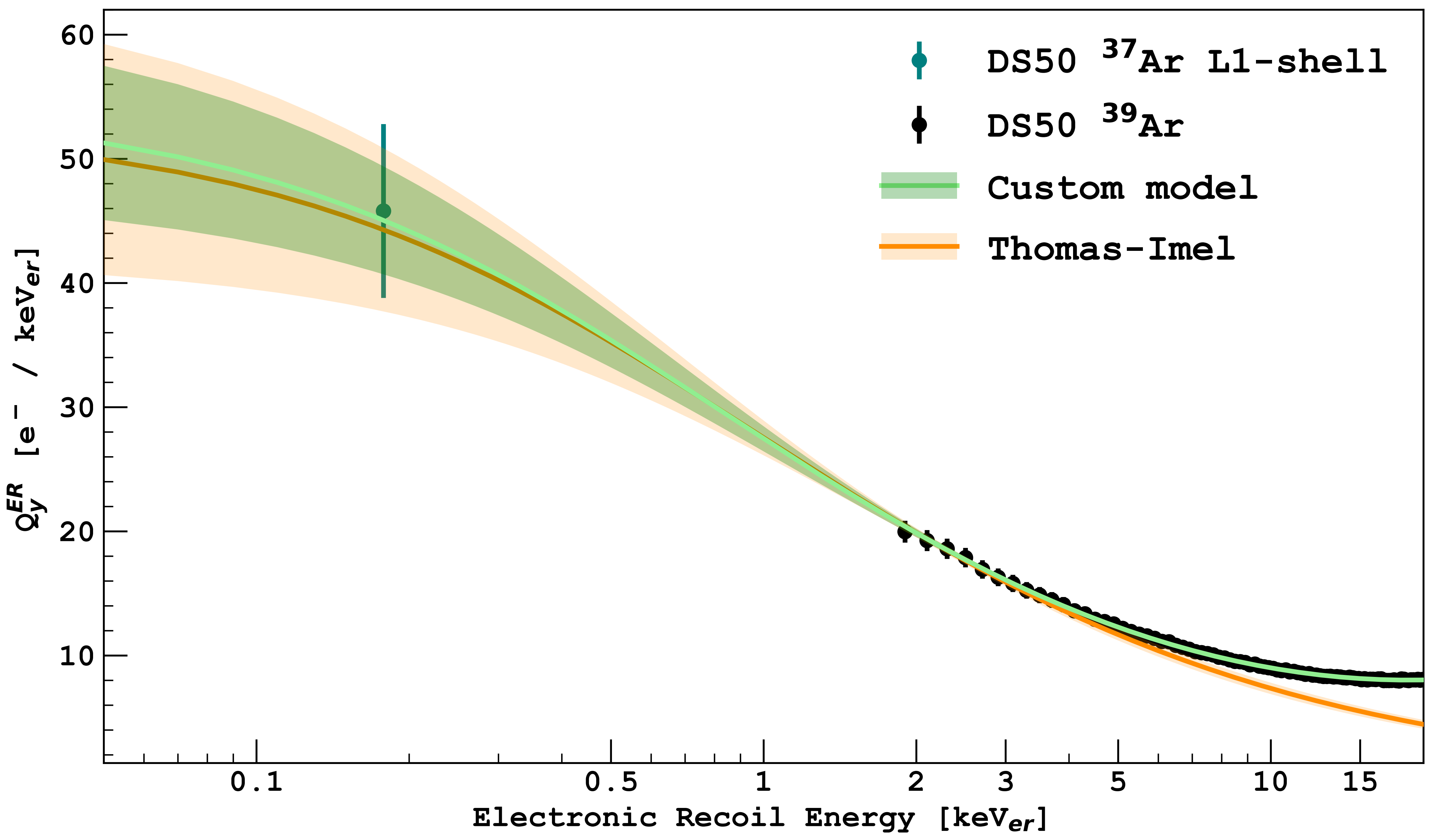
- Quality cuts
  - pile-up of multiple pulses (95% @ 4 Ne / 99% @ 15 Ne)
- Selection cuts
  - Fiducialization against external bg (41%)
  - S2/S1 against S2's from alphas on the walls (99%)
  - Time veto agains spurious (or "single") electrons (97%)

Ionization Response to Electronic Recoils

Thomas-Imel + extended custom model

$$Q_y^{ER} = \left(\boxed{\frac{1}{\gamma}} + \boxed{p_0\,(E_{er}/\mathrm{keV}_{er})^{p_1}}\right) \boxed{\frac{\ln(1+\gamma\,\rho\,E_{er})}{E_{er}}}$$





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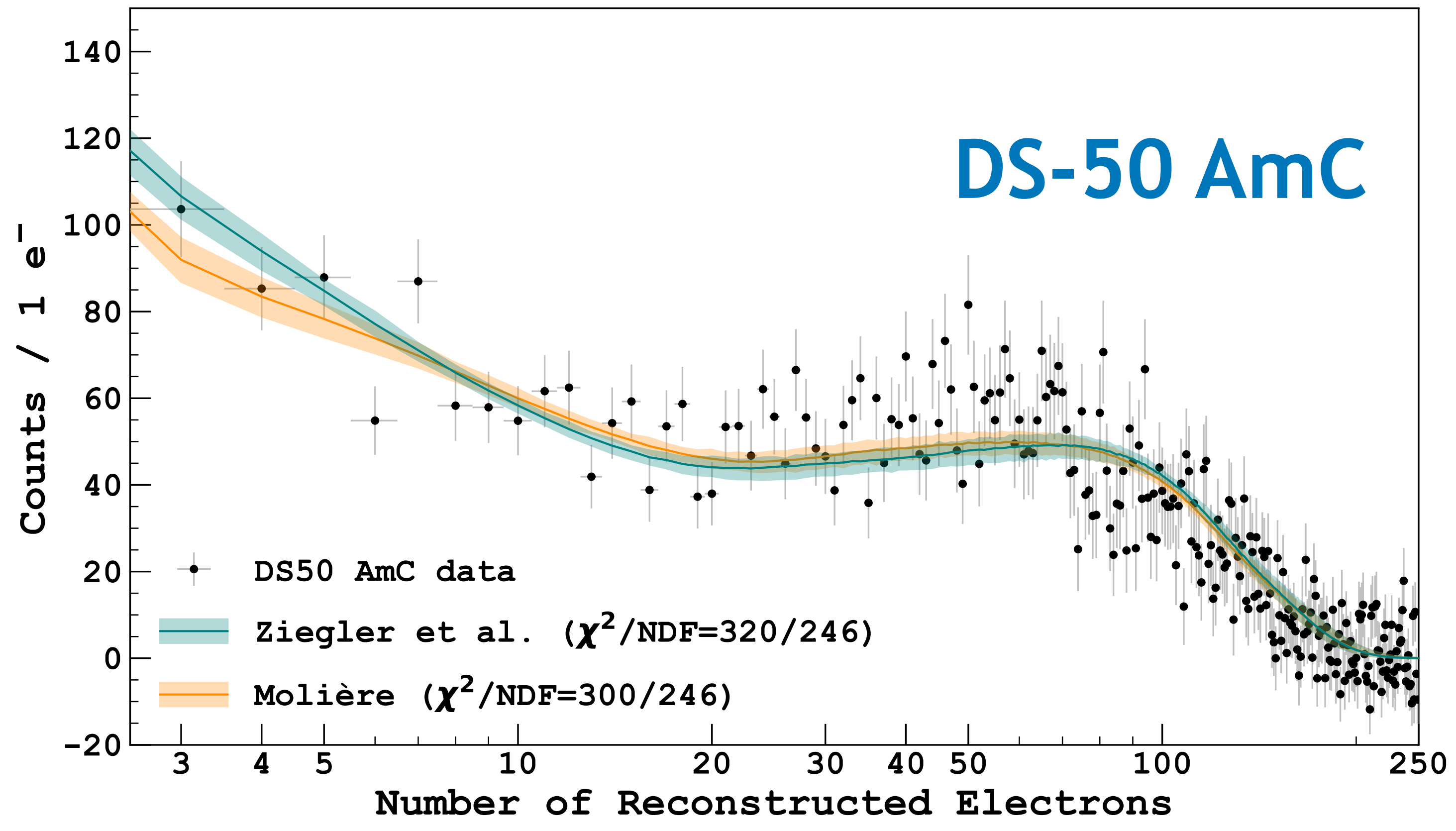
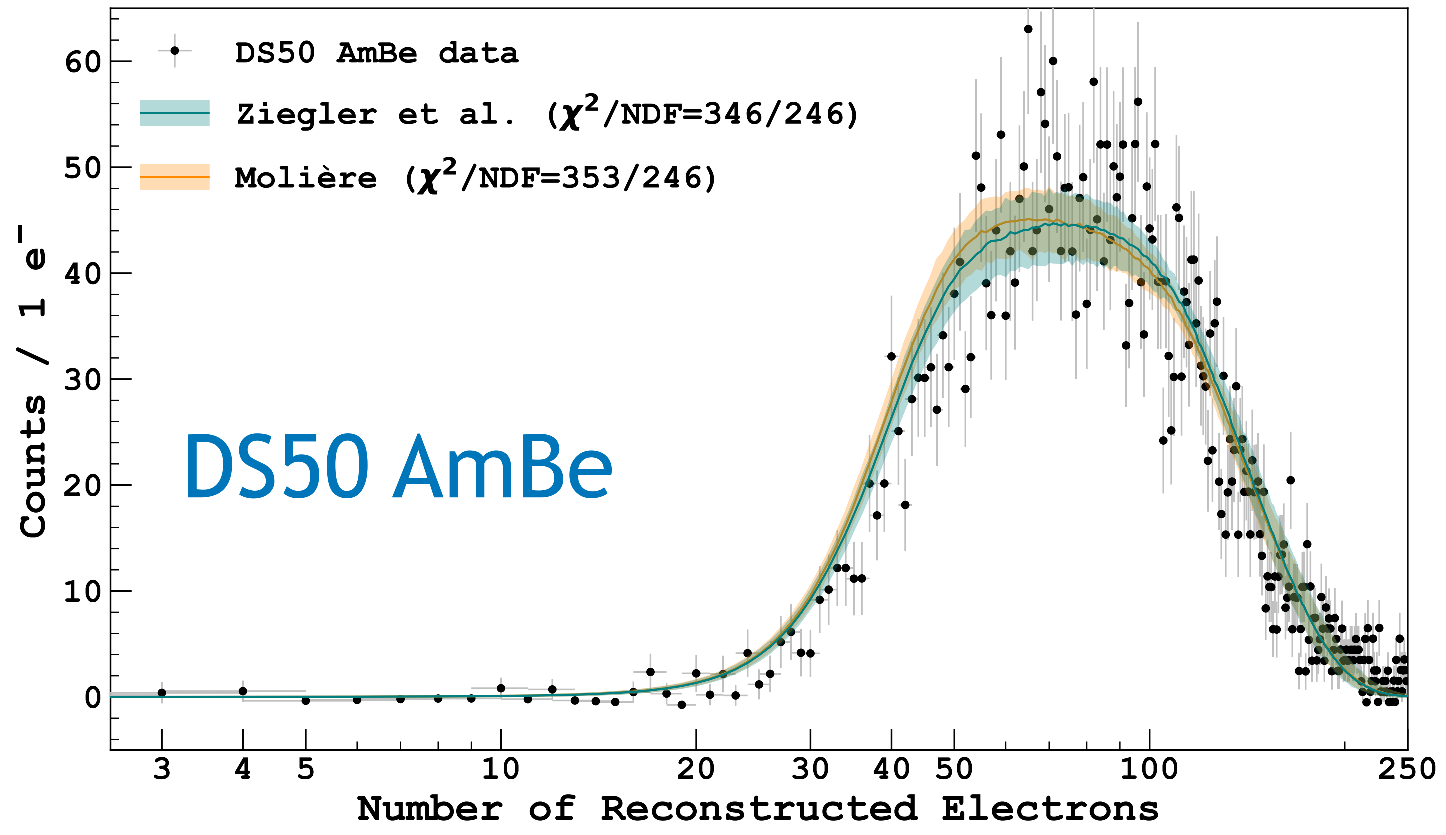
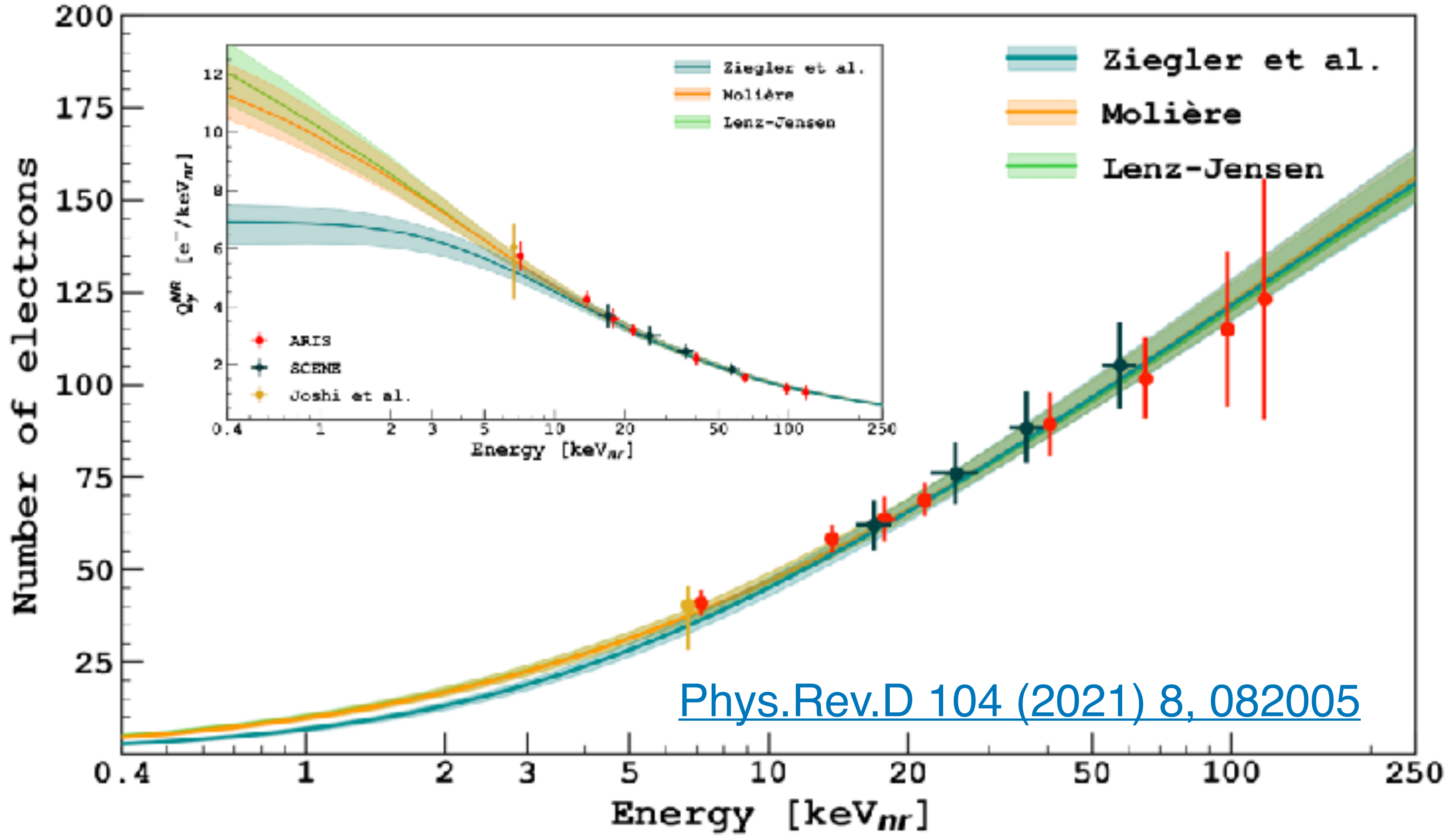
Ionization Response to Nuclear Recoils

Global fit to **DS-50 calibration data** with neutrons sources + **external datasets** (ARIS and SCENE)





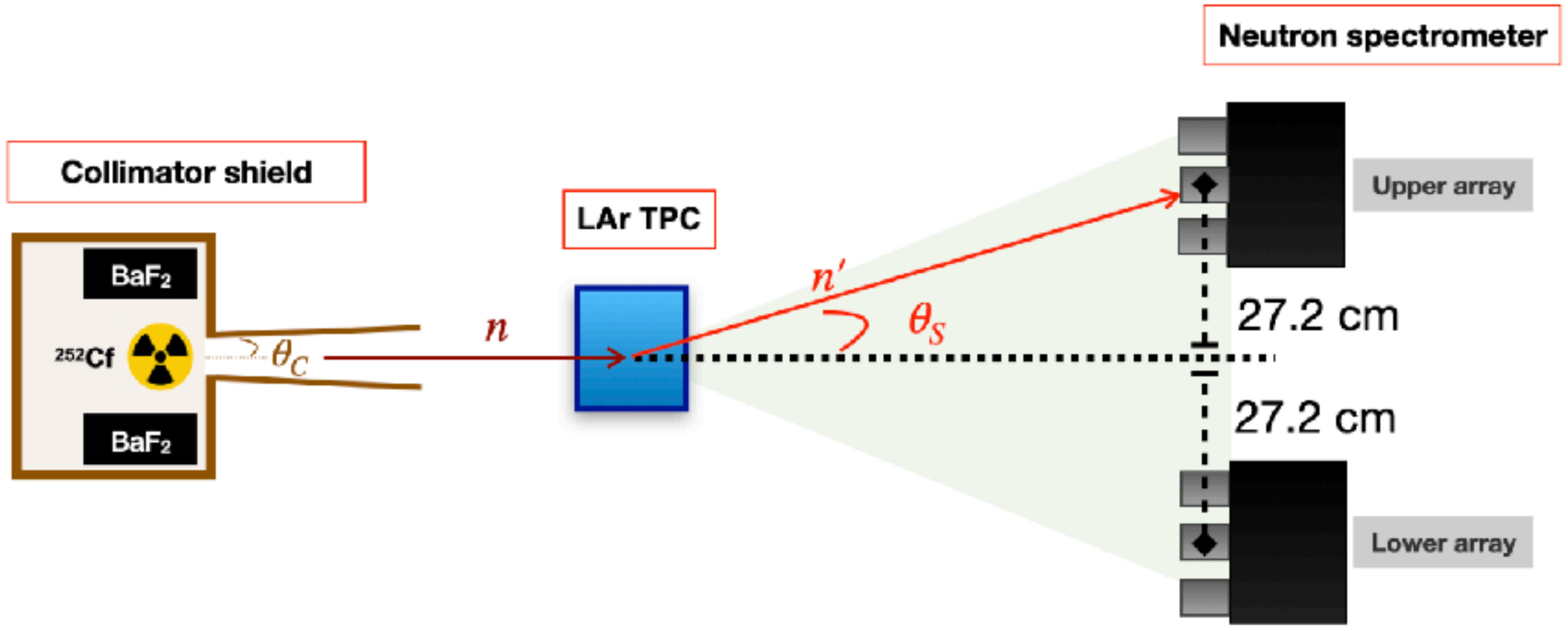


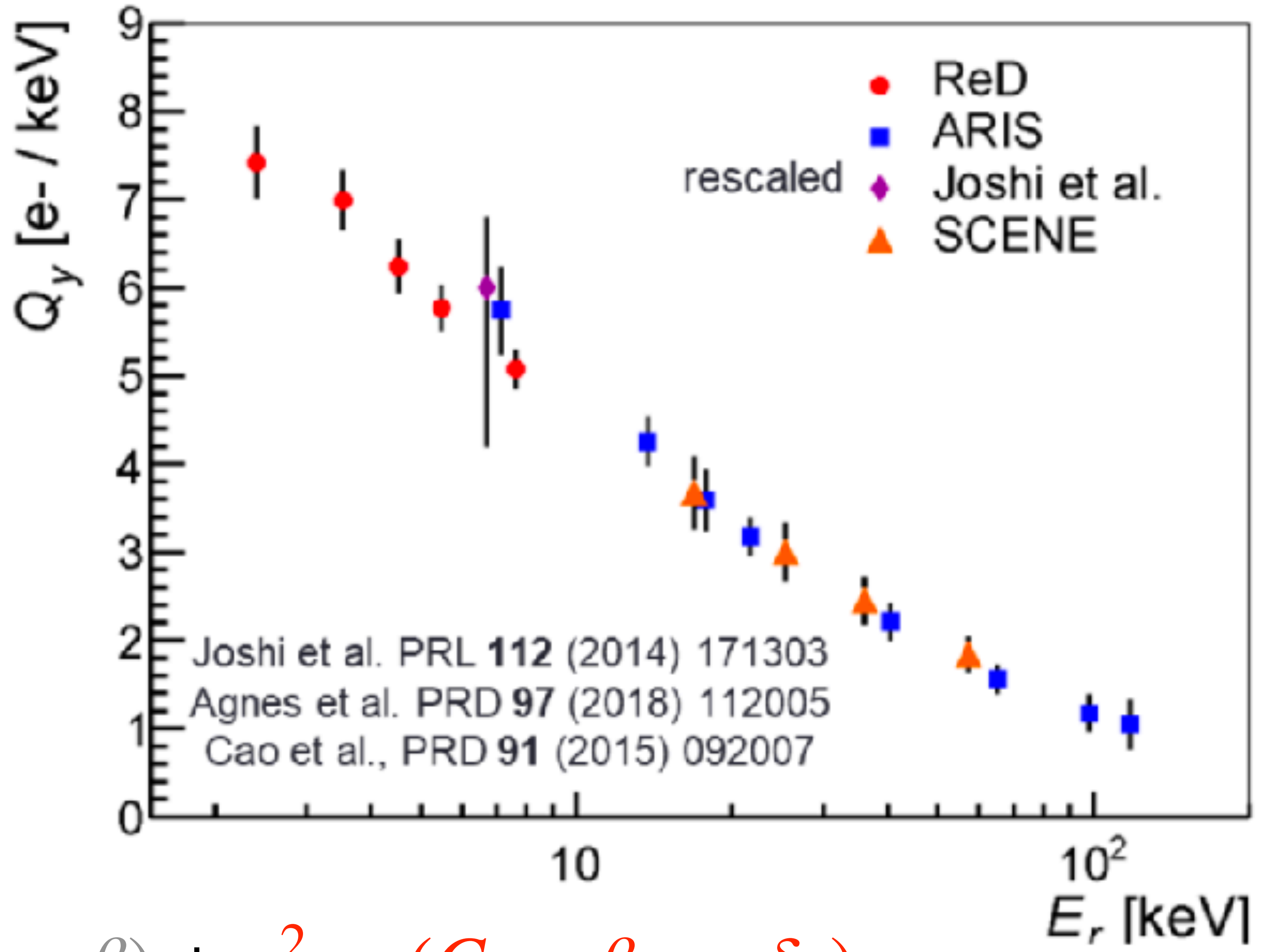
Thomas-Imel Box Model

$$f_q(E_{nr}) = \frac{F}{E_{nr}\, C_{\text{box}}} \ln\left[1 + \frac{C_{\text{box}}}{F} \cdot \beta \cdot \frac{\epsilon(E_{nr})\, s_e(\epsilon)}{s_e(\epsilon) + s_n(\epsilon)}\right]$$

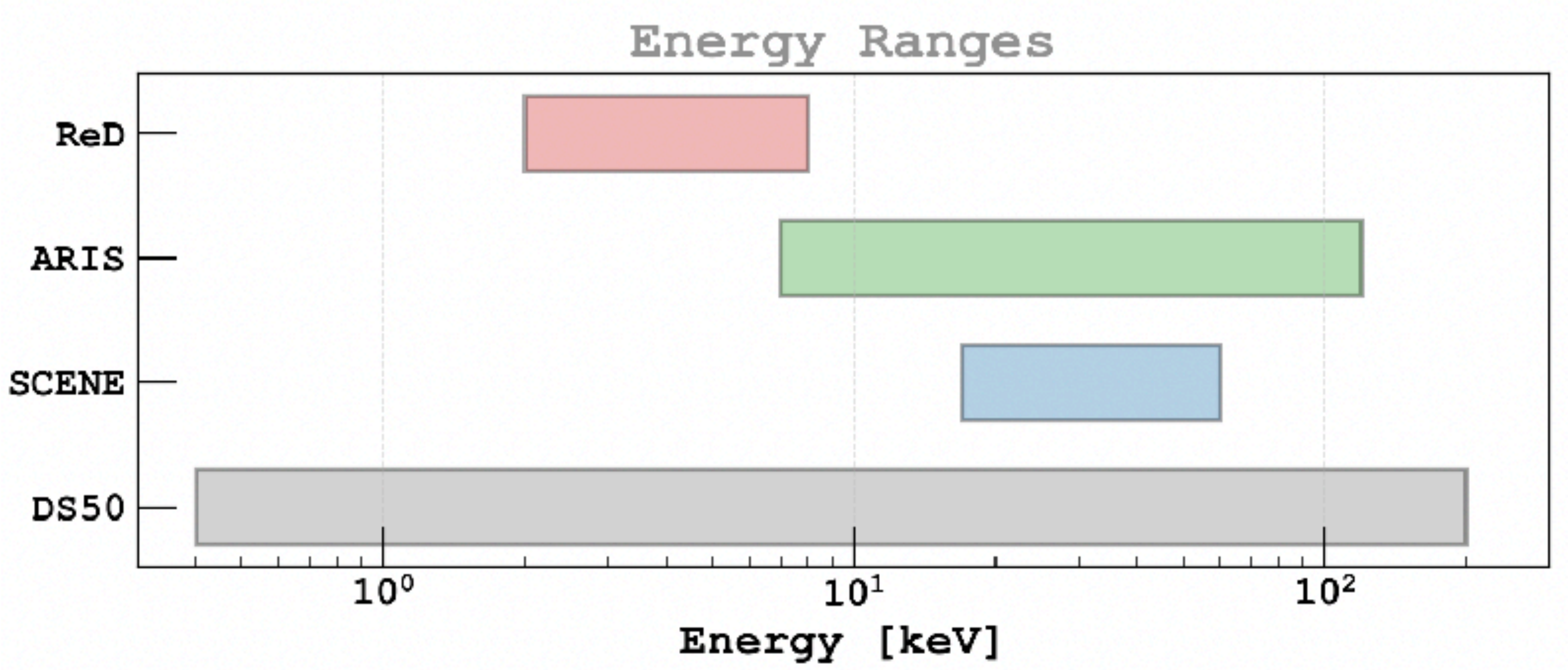
In 2023, Ziegler's screening function chosen for sensitivity studies

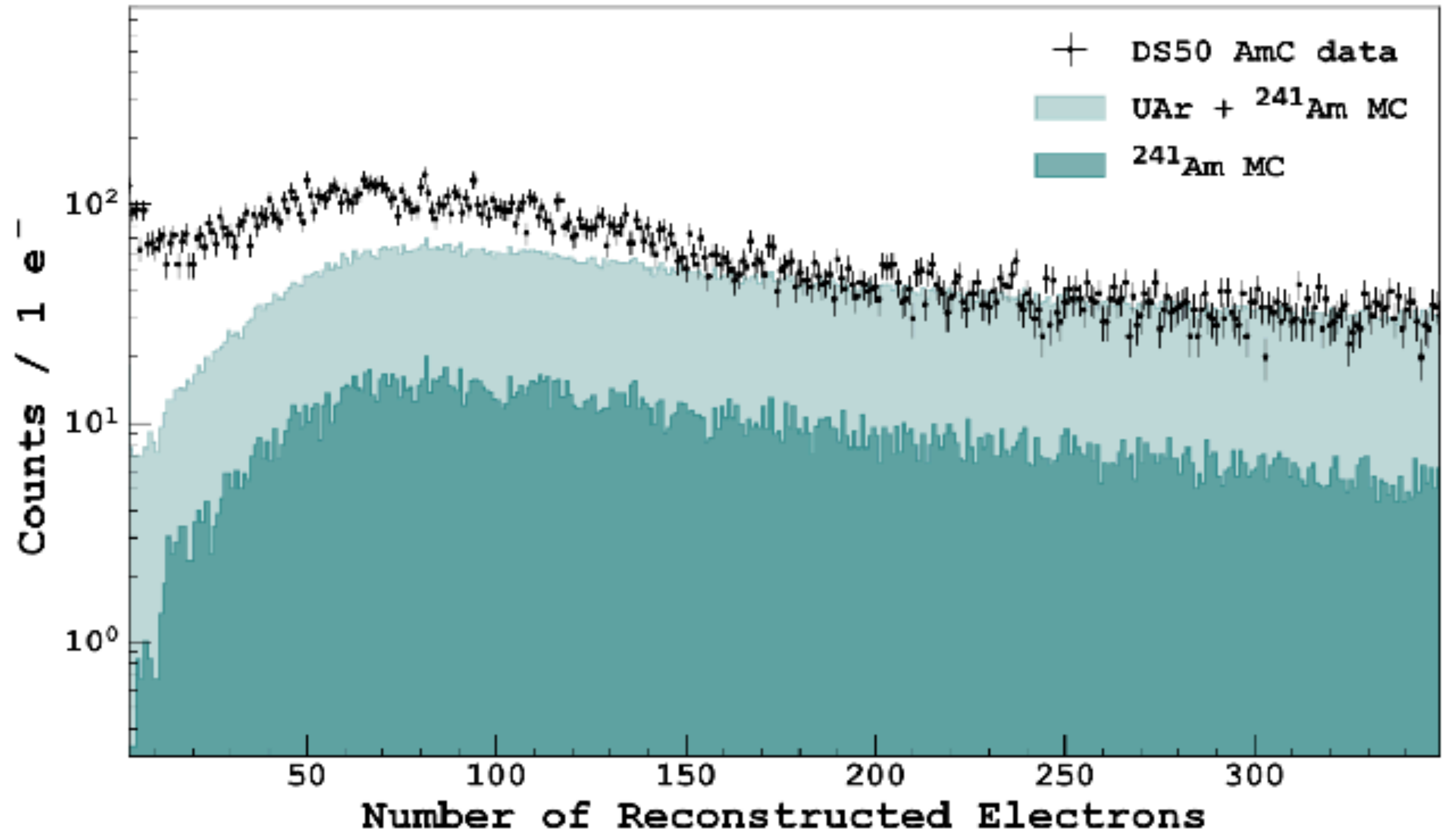
Including ReD data



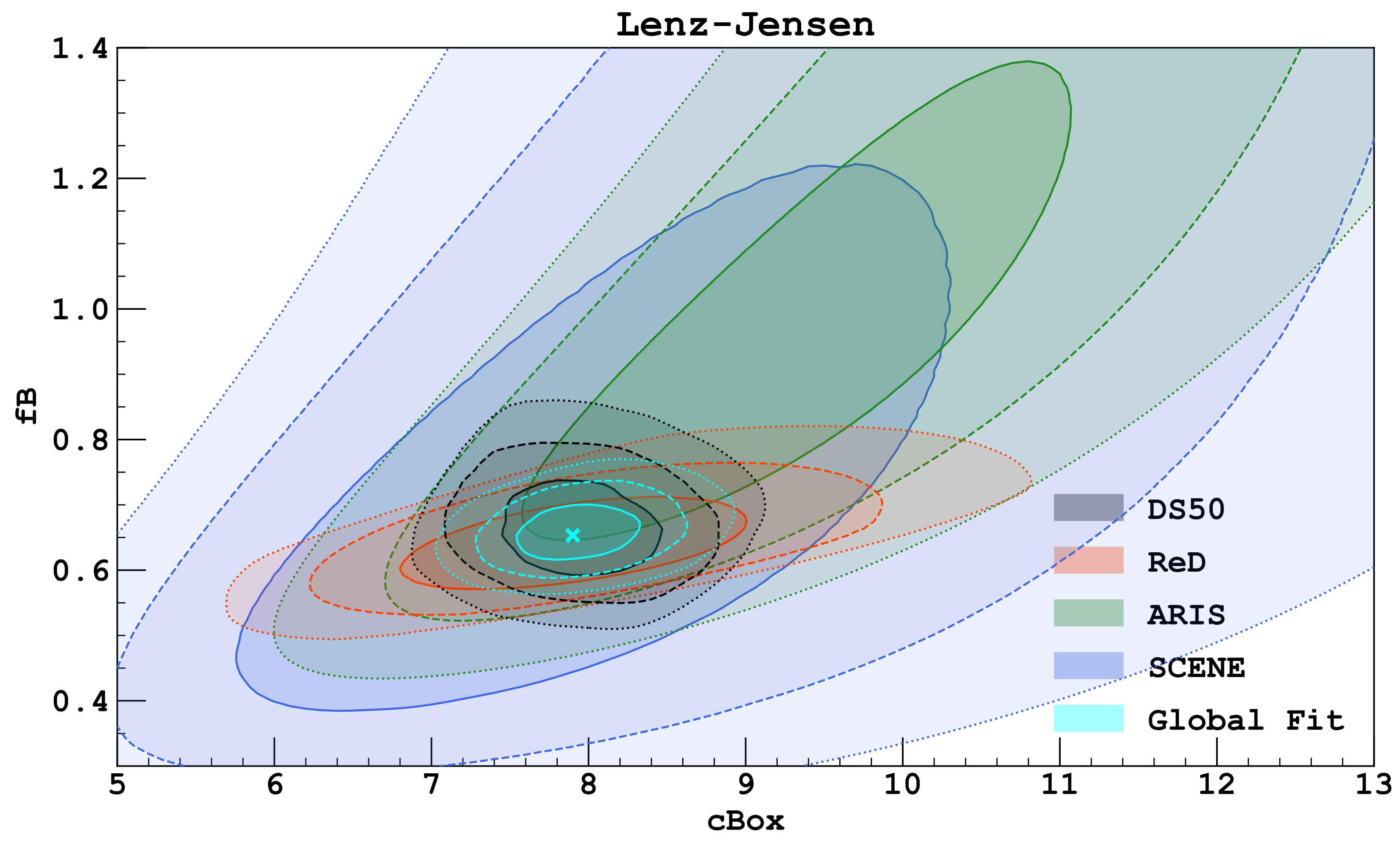


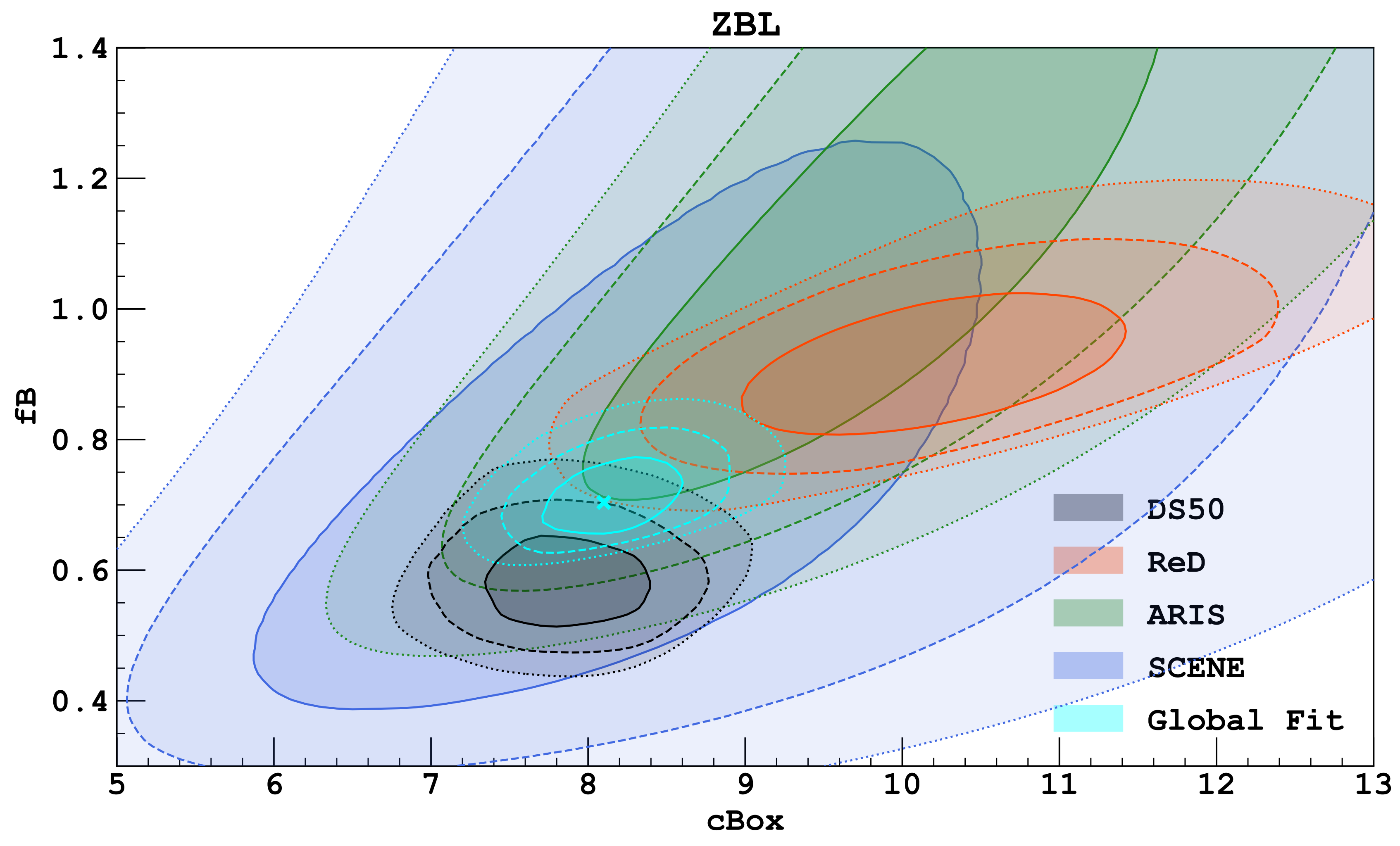
$$\chi^2_{\text{tot}}(C_{\text{box}},\beta)=\chi^2_{\text{ARIS}}(C_{\text{box}},\beta)+\chi^2_{\text{SCENE}}(C_{\text{box}},\beta)+\chi^2_{\text{DS50}}(C_{\text{box}},\beta)+\chi^2_{\text{ReD}}(C_{\text{box}},\beta;g_2,\delta z)$$

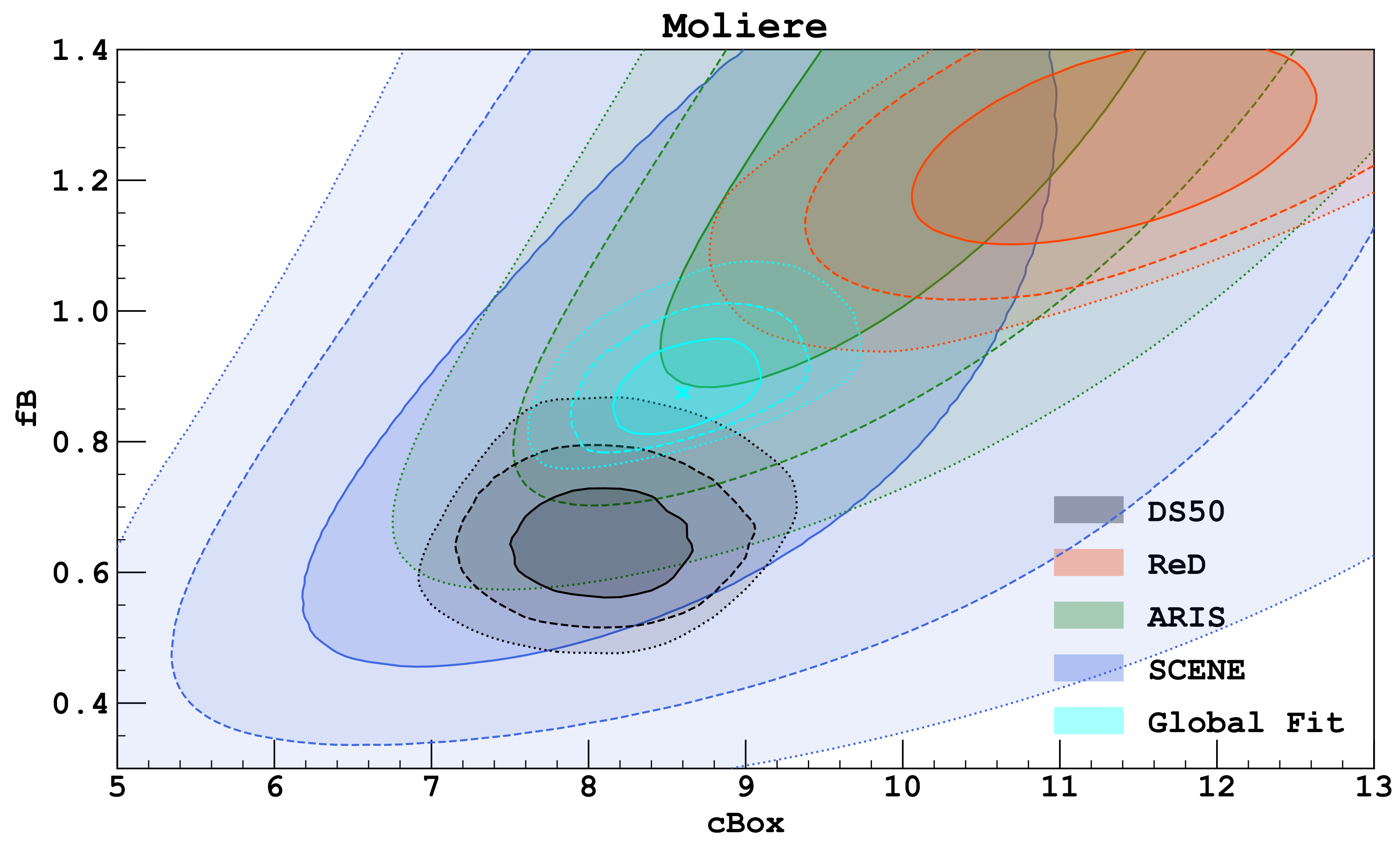




Rejecting Molière and ZBL





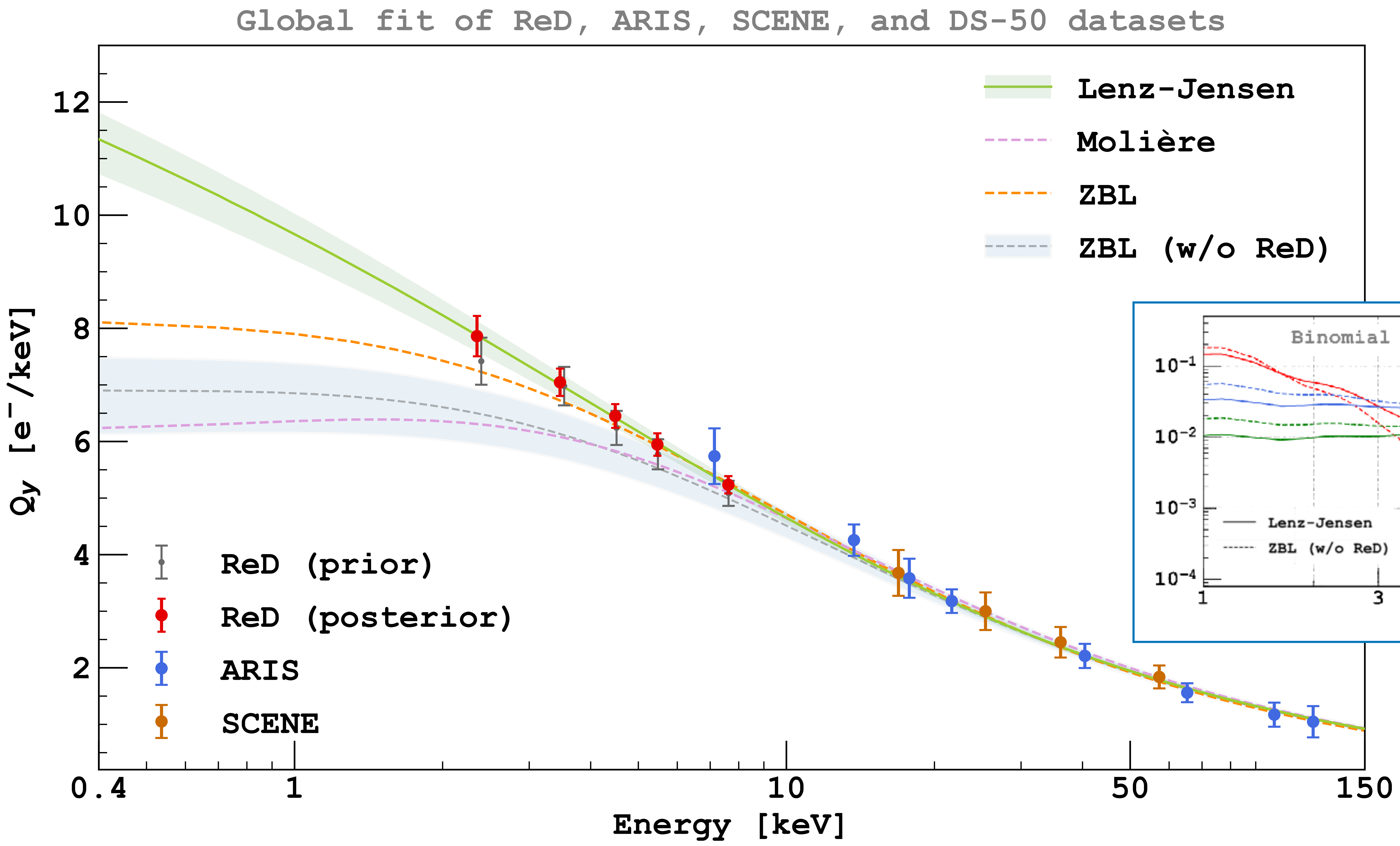


- Lenz-Jensen over ZBL: $\log_{10}$ (Bayes Factor) = 3.8
- Lenz-Jensen over Molière: $\log_{10}$ (Bayes Factor) = 7.2

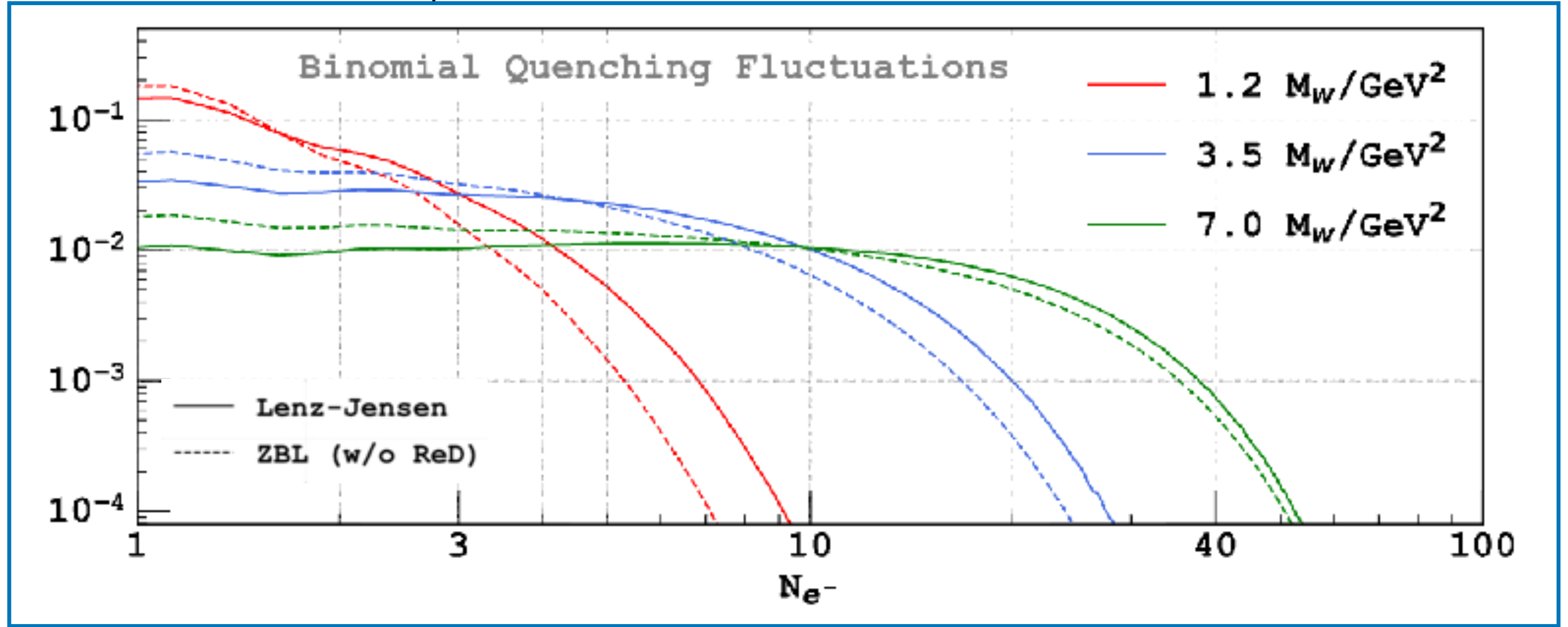
ZBL and Molière: rejected

$\log_{10}$BF	Jeffrey (1961)	Kass & Raftery (1995)
Negligible	<0.5	<0.5
Substantial	0.5-1	0.5-1.3
Strong	1-2	1.3-2.2
Decisive	>2	>2.2

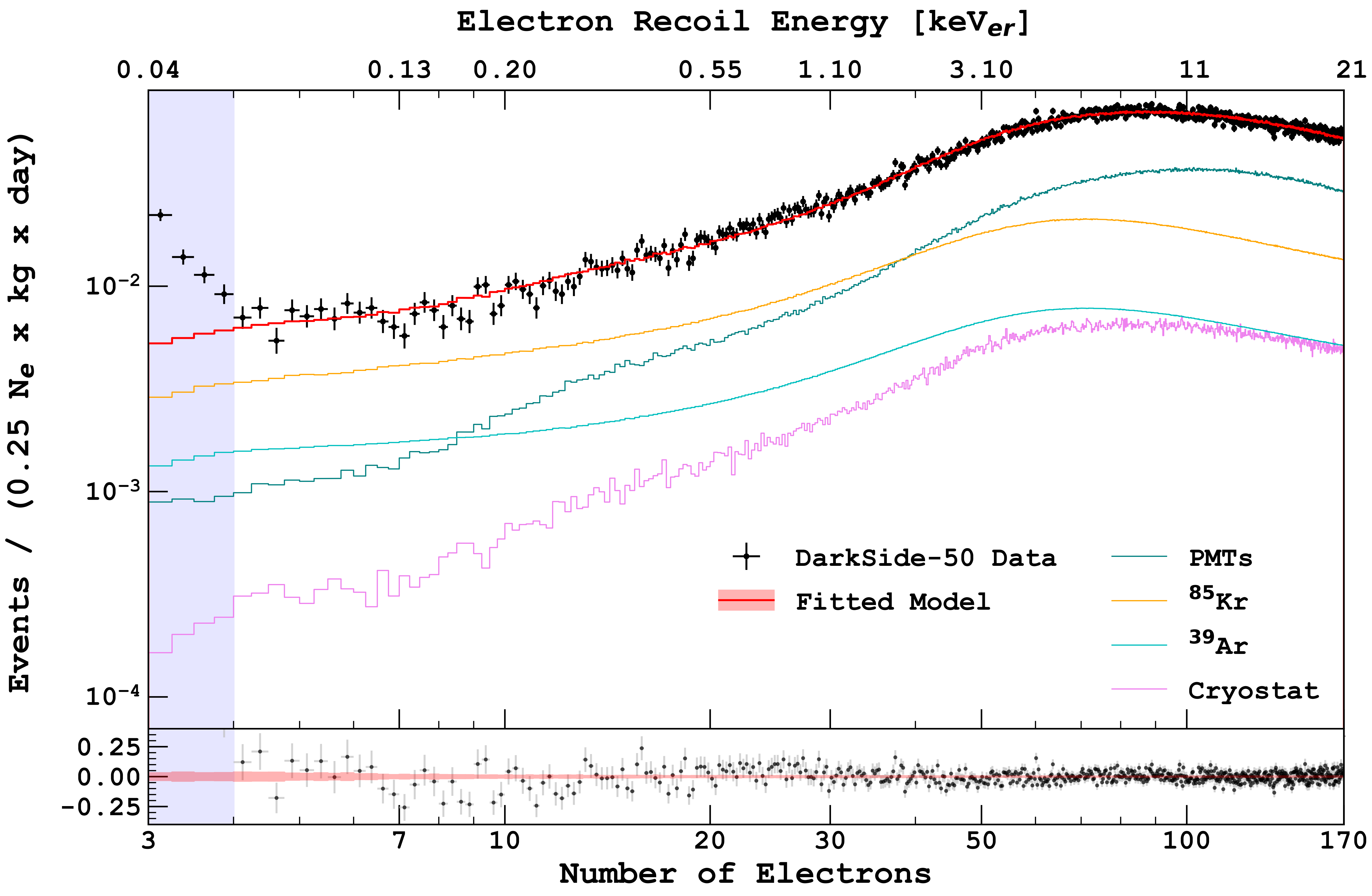
Ionization Response to Nuclear Recoils

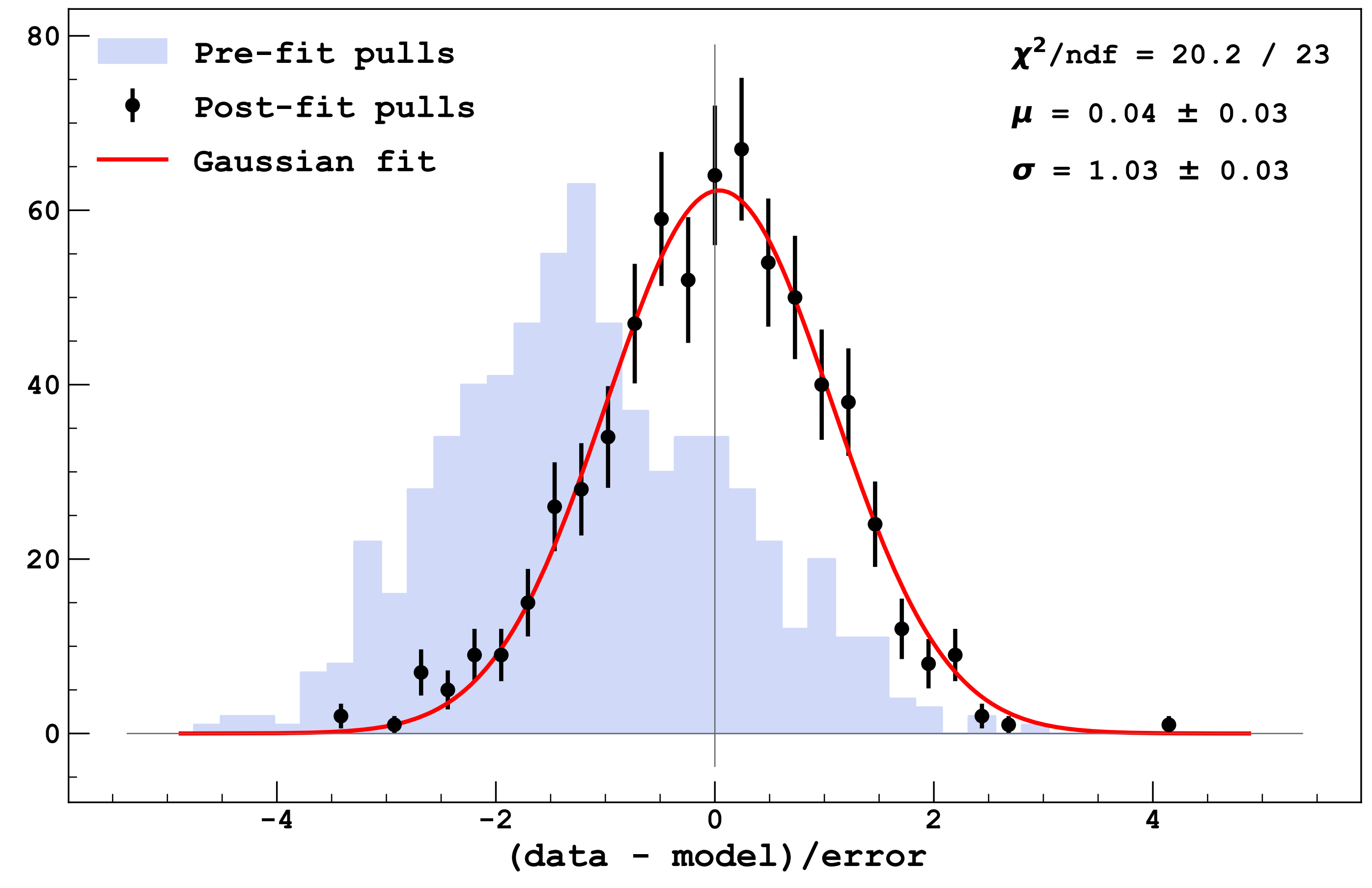


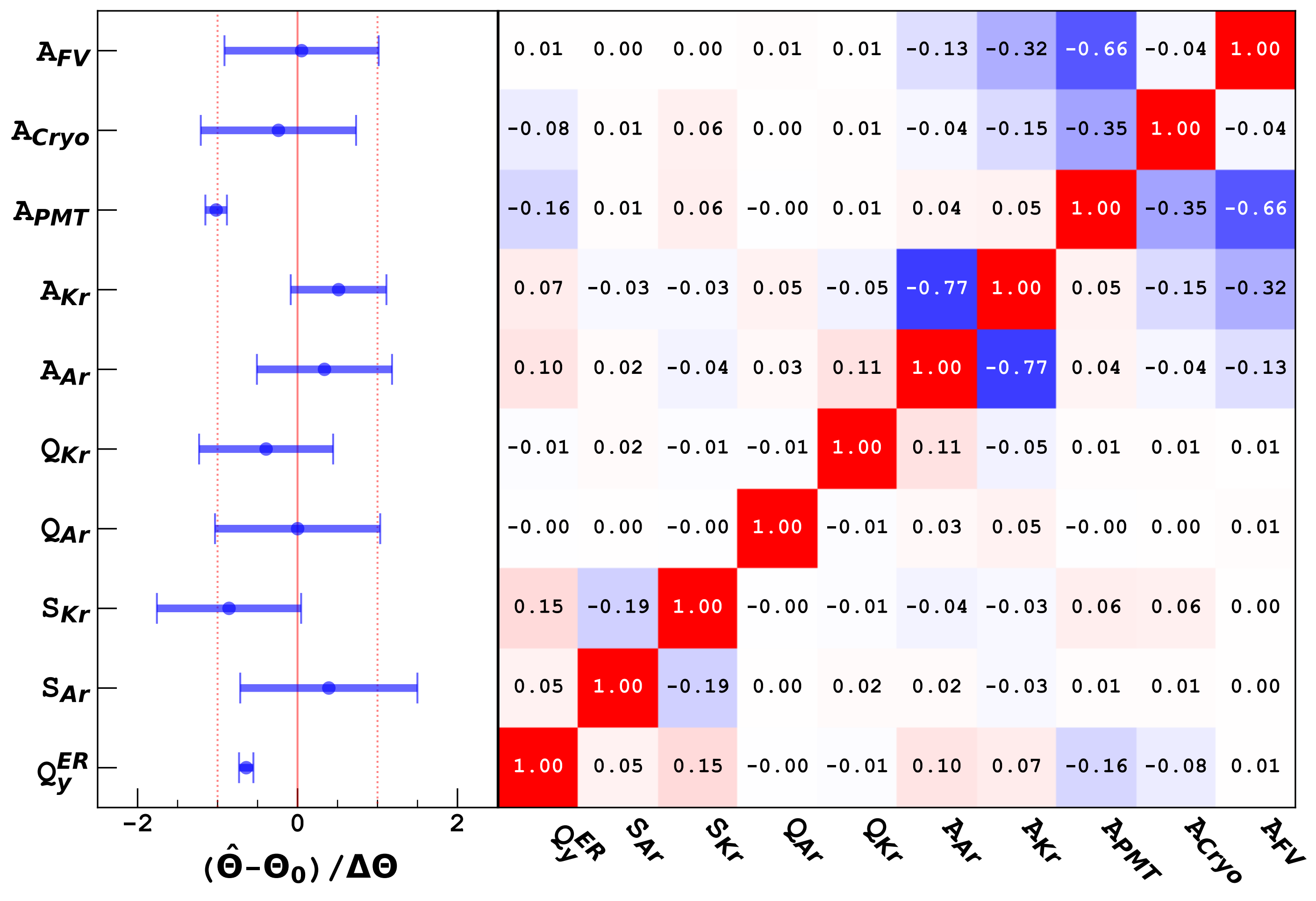
WIMP signal



Background-Only Fit

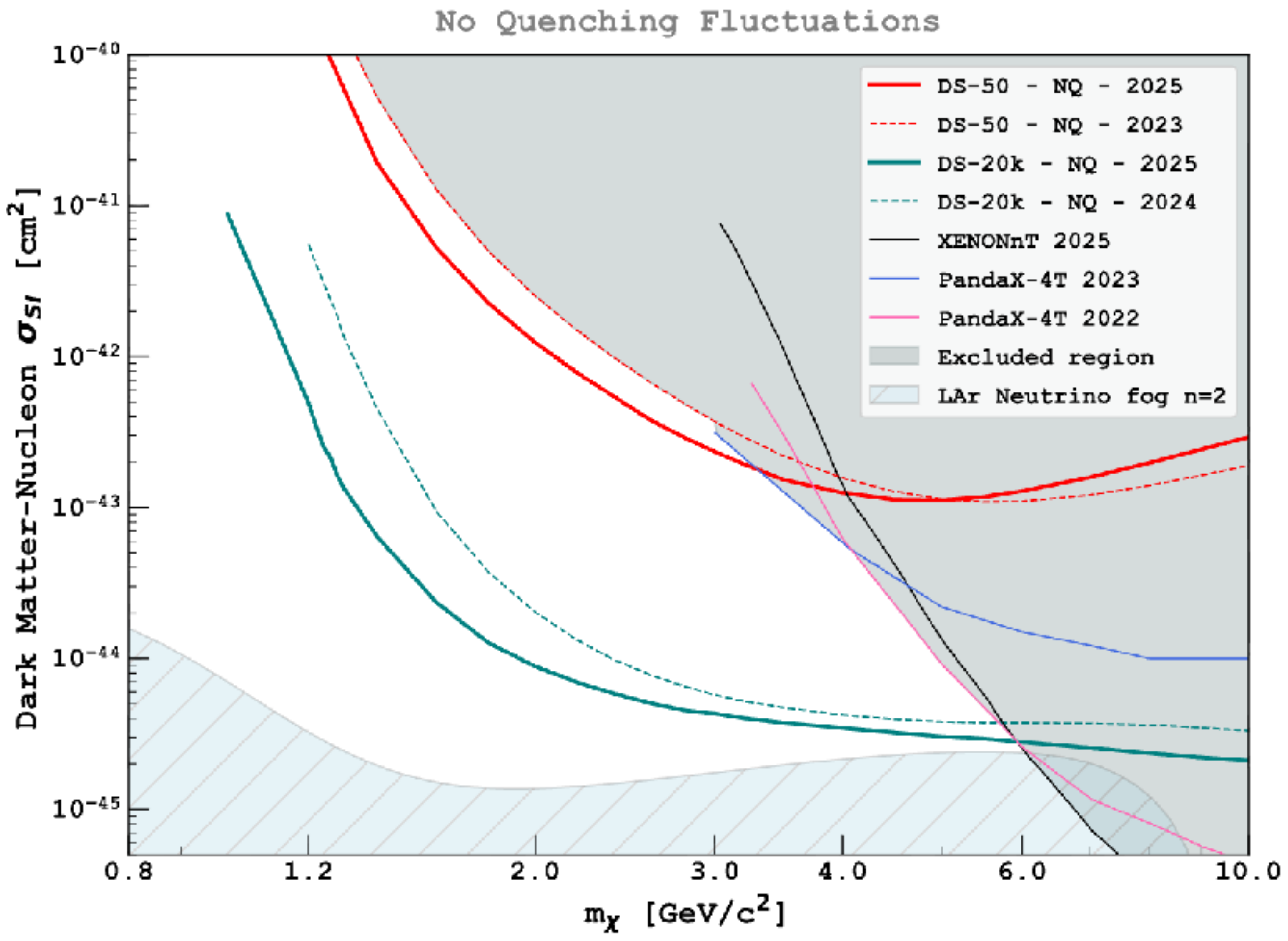


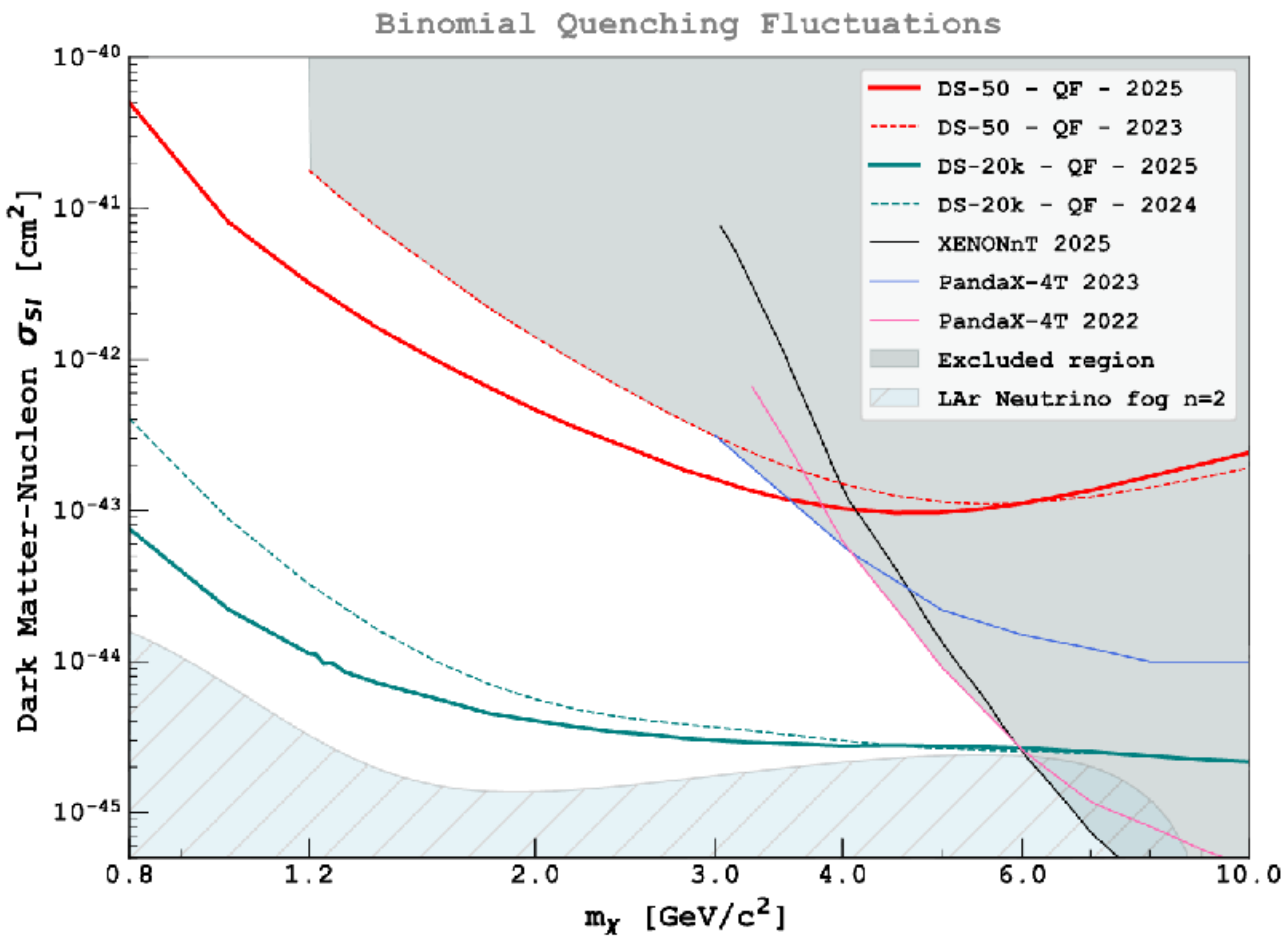




Tritium activity <1 μBq/kg (90% CL)

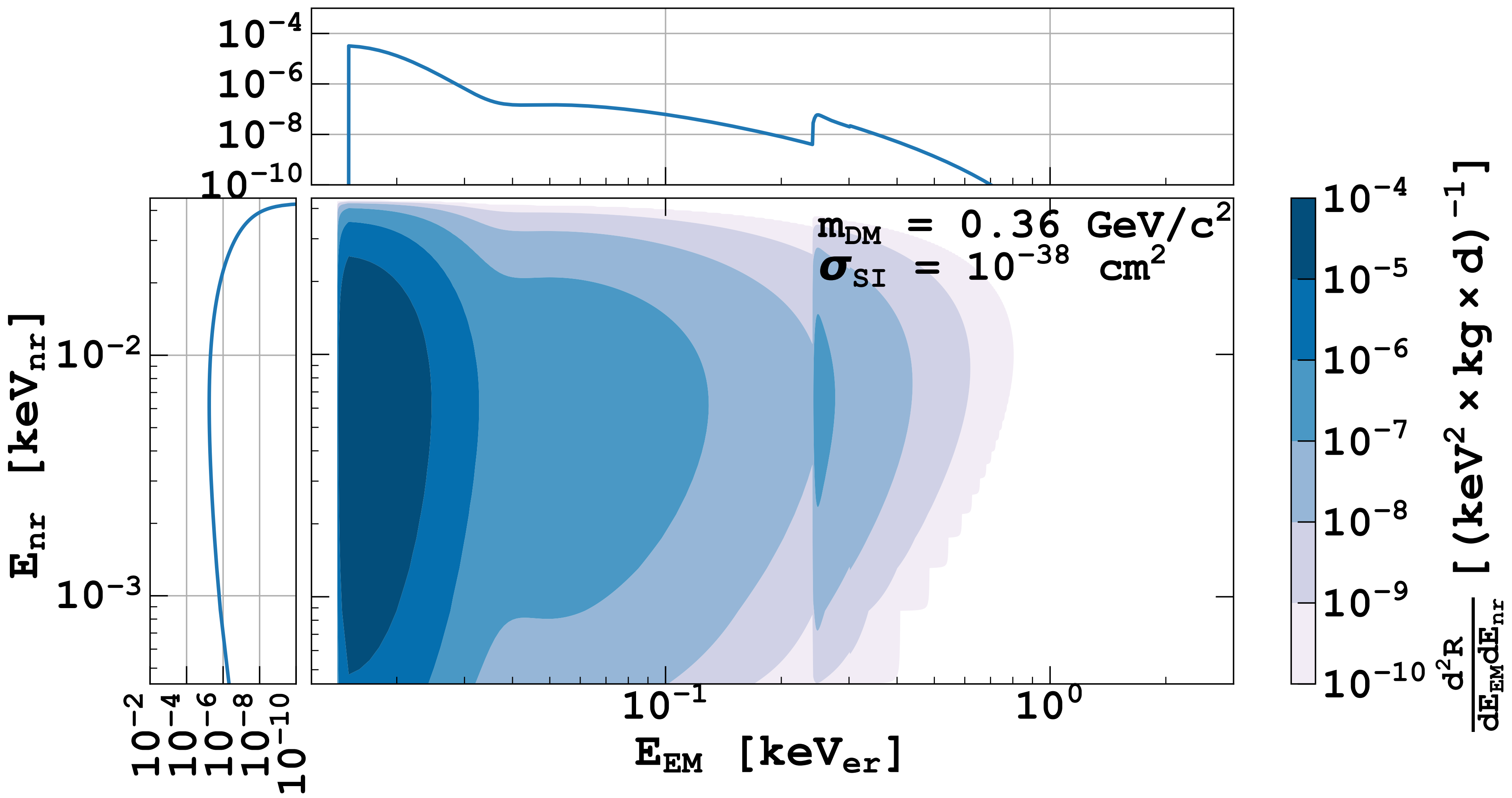
Low-mass WIMP limits

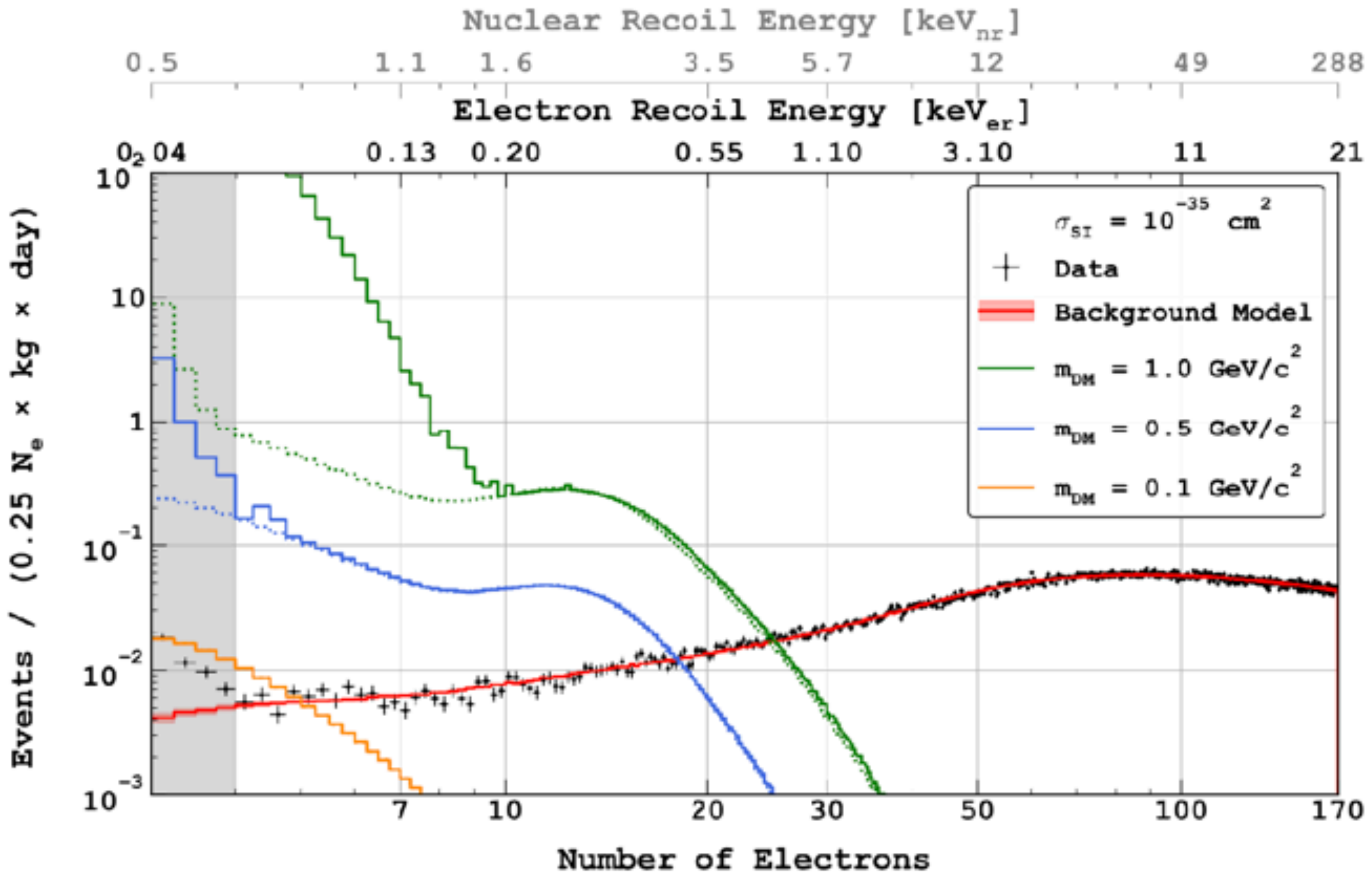


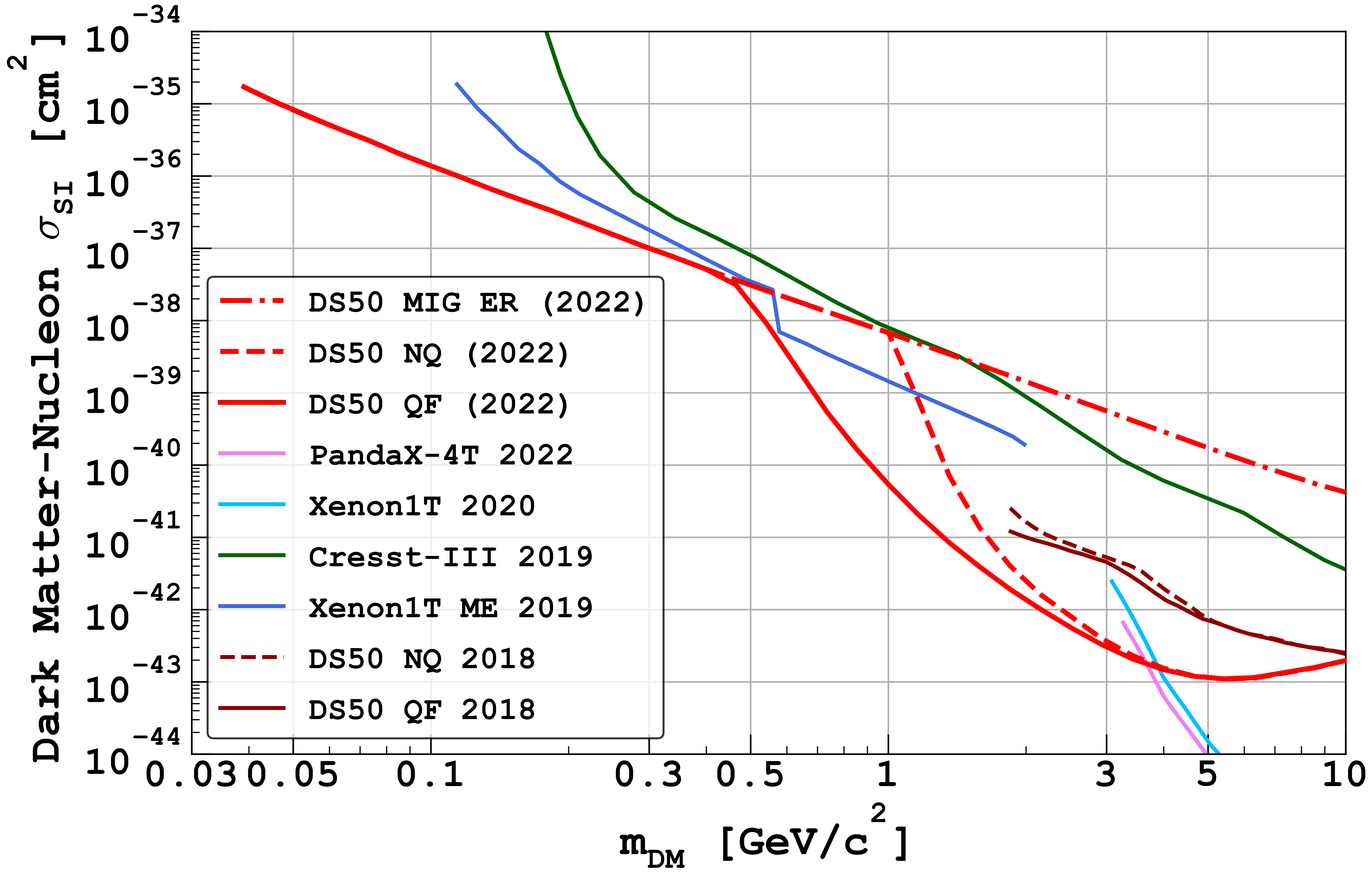


DarkSide-20k: 10 years exposure and 2 e- threshold (spurious electrons included in the background model)

The Migdal Effect



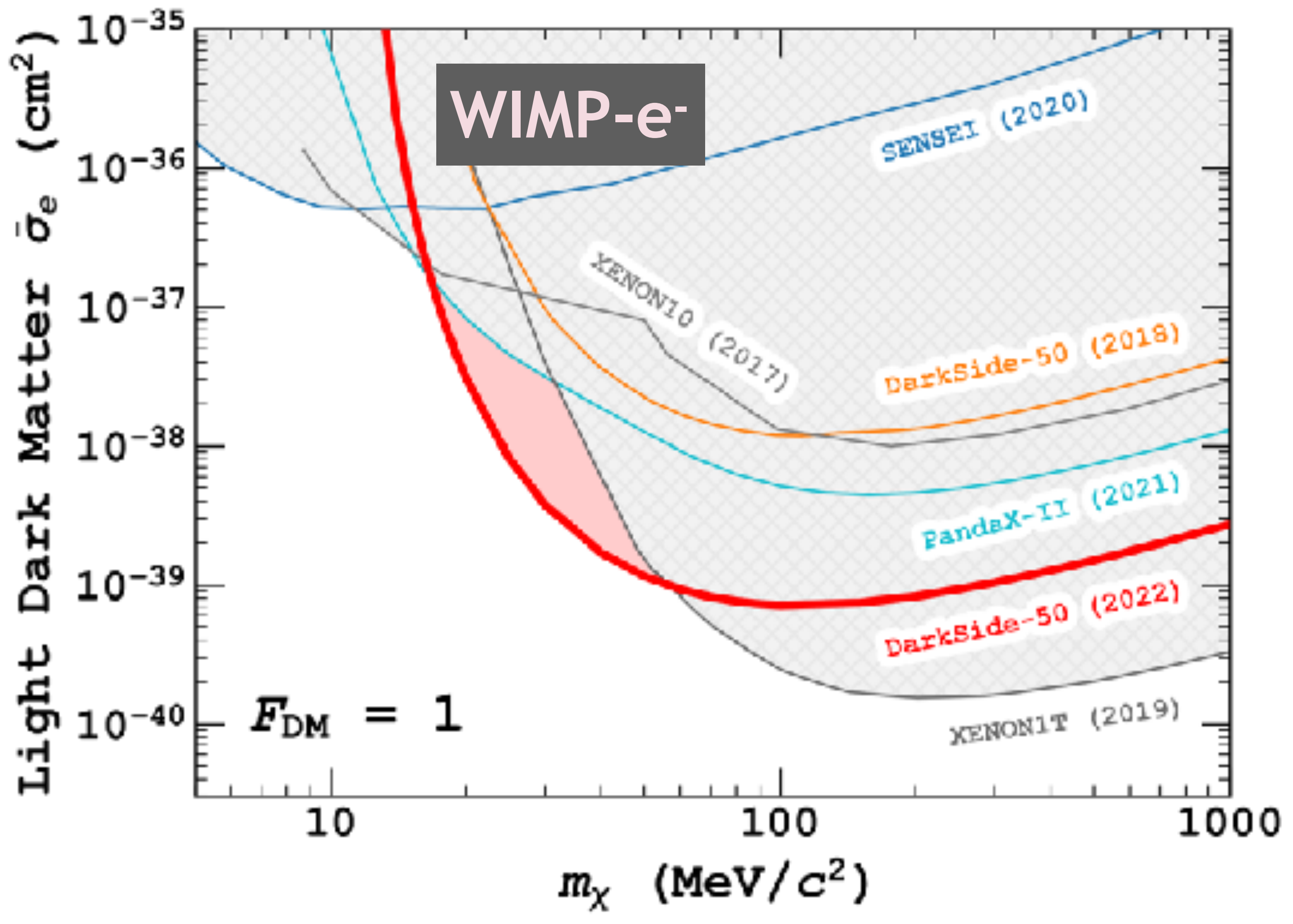


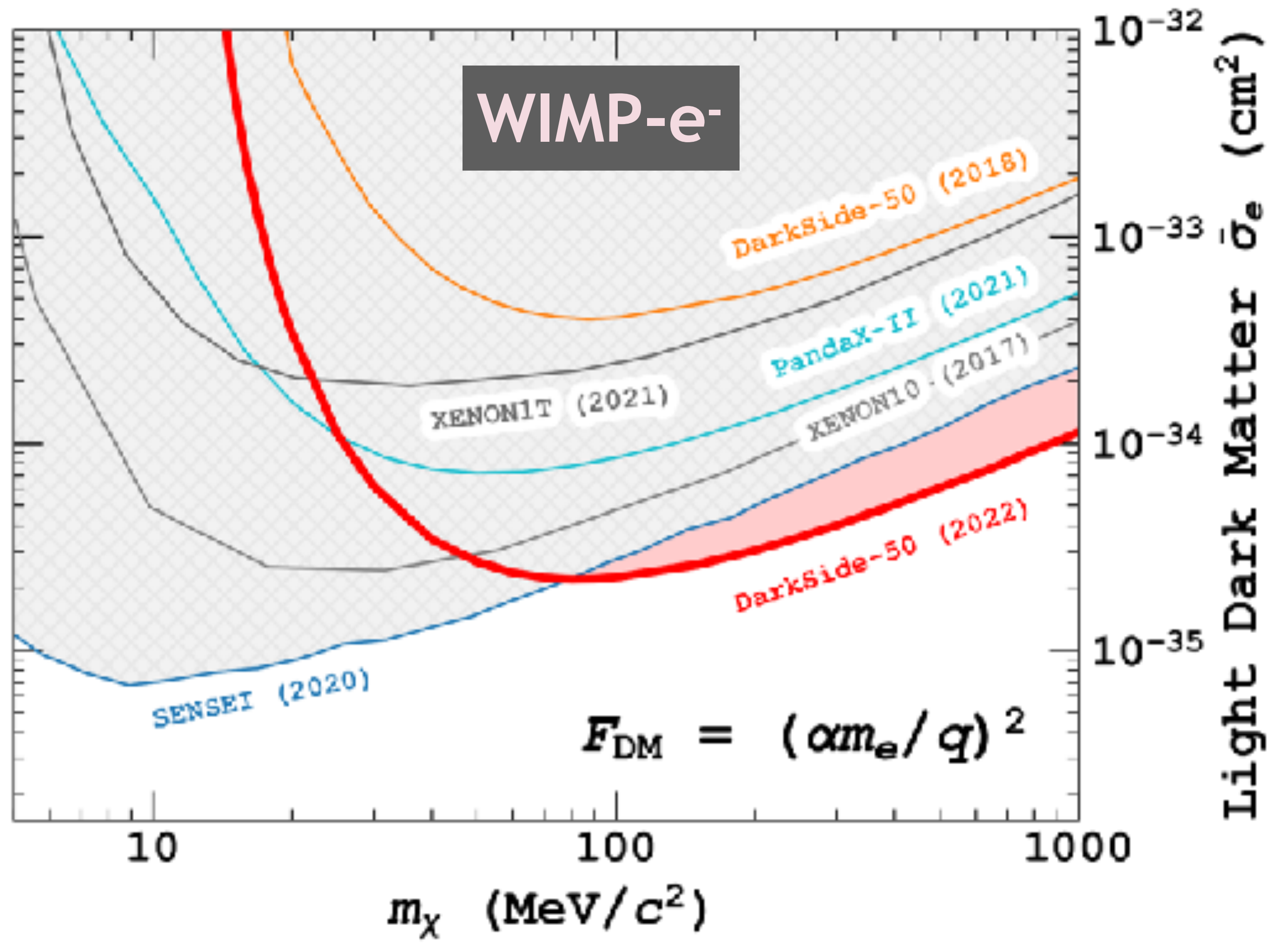


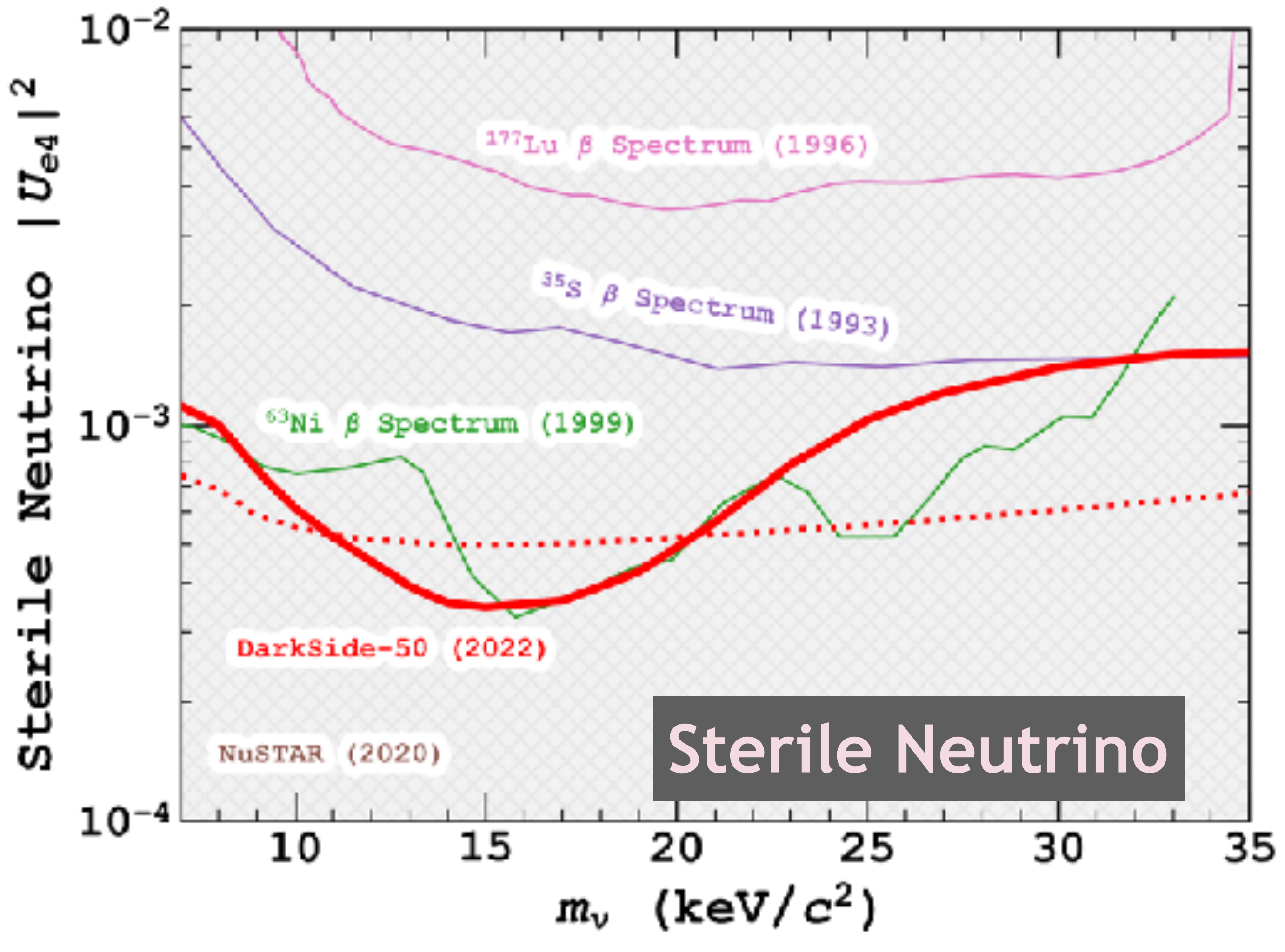
Results confirmed by using **Bayesian Networks** ([arXiv:2302.01830](https://arxiv.org/abs/2302.01830))

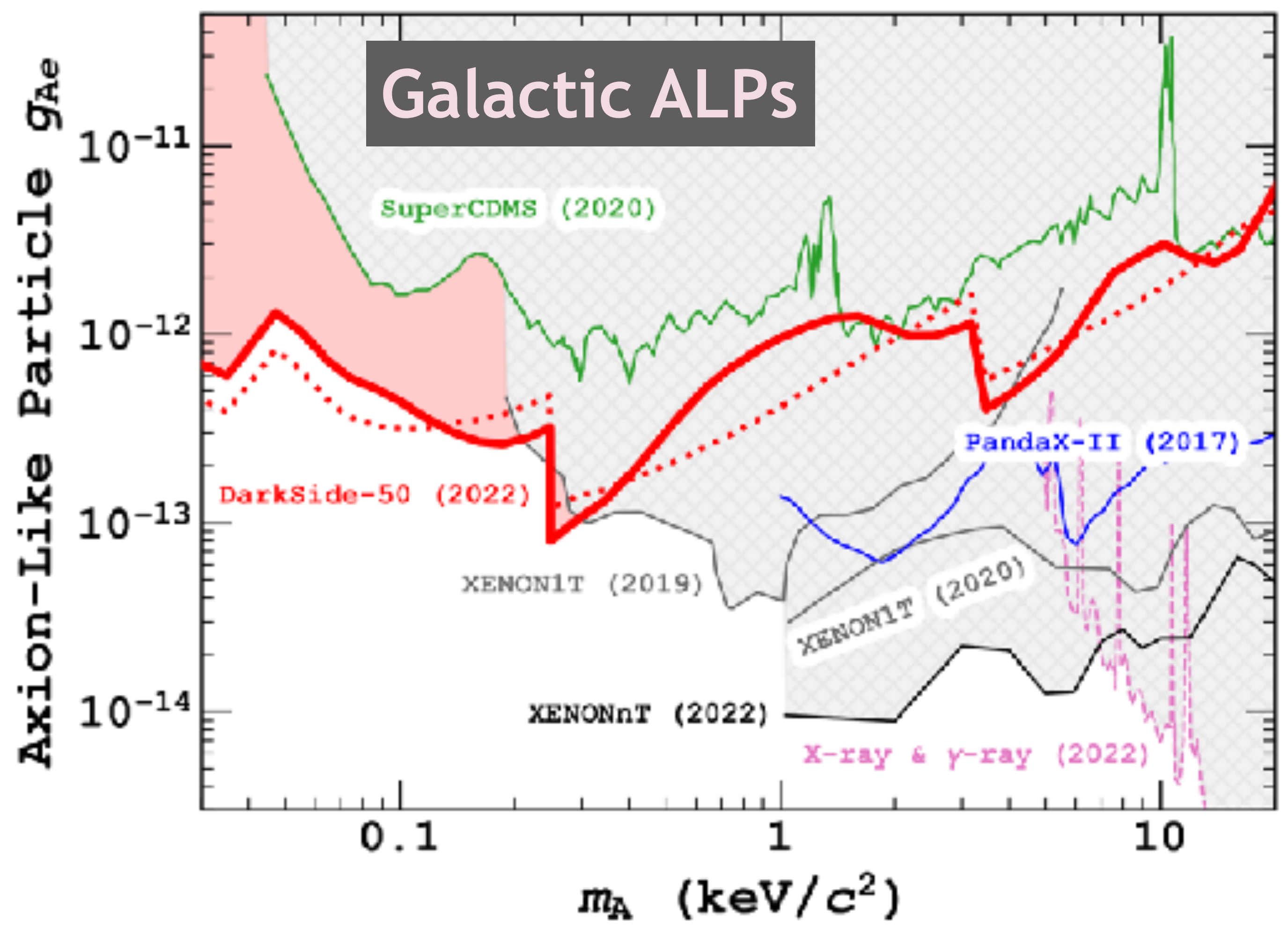
- detector response model included in the likelihood function
- Markov Chain Monte Carlo for posterior probability

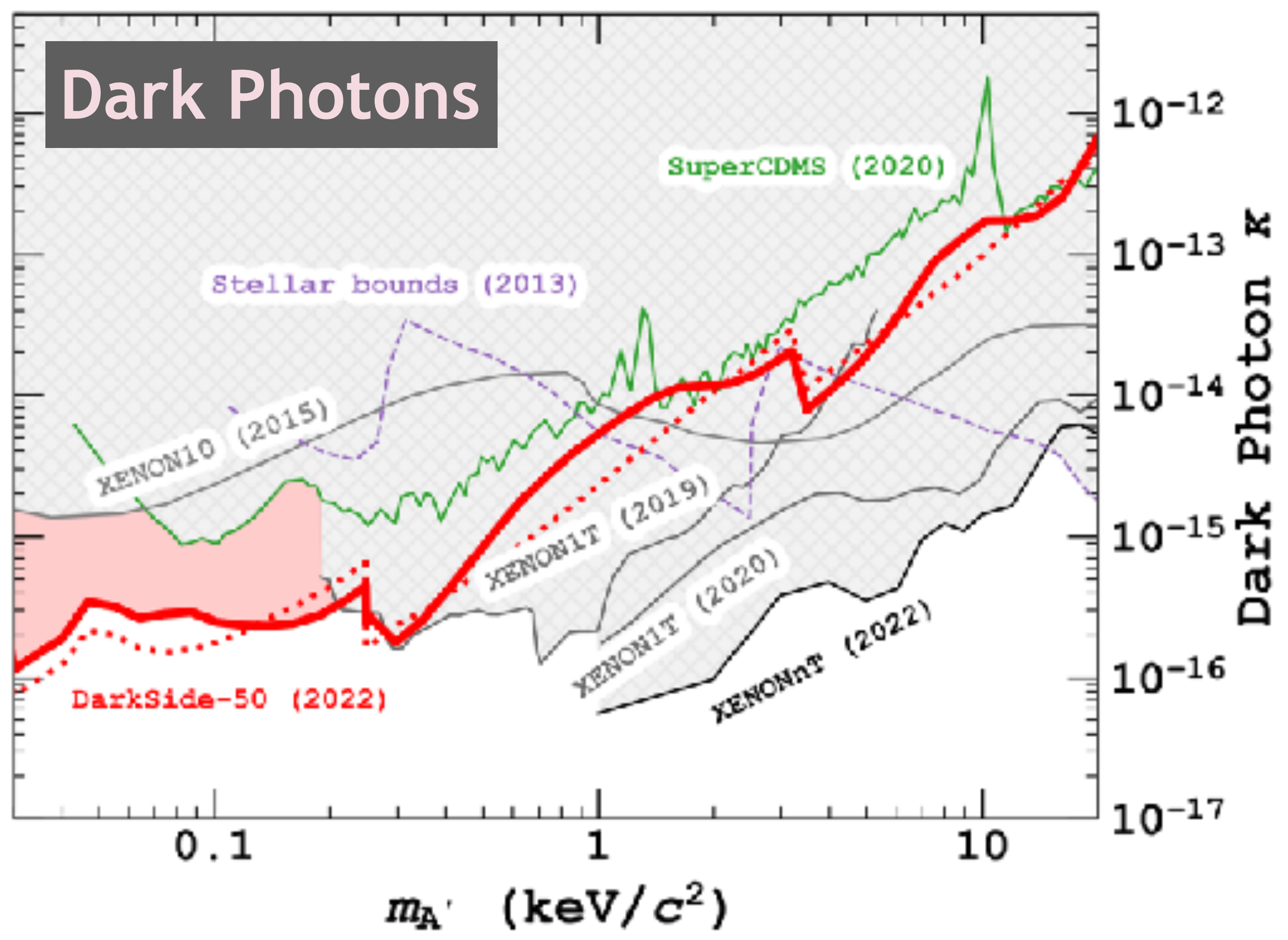
Leptophilic Dark Matter







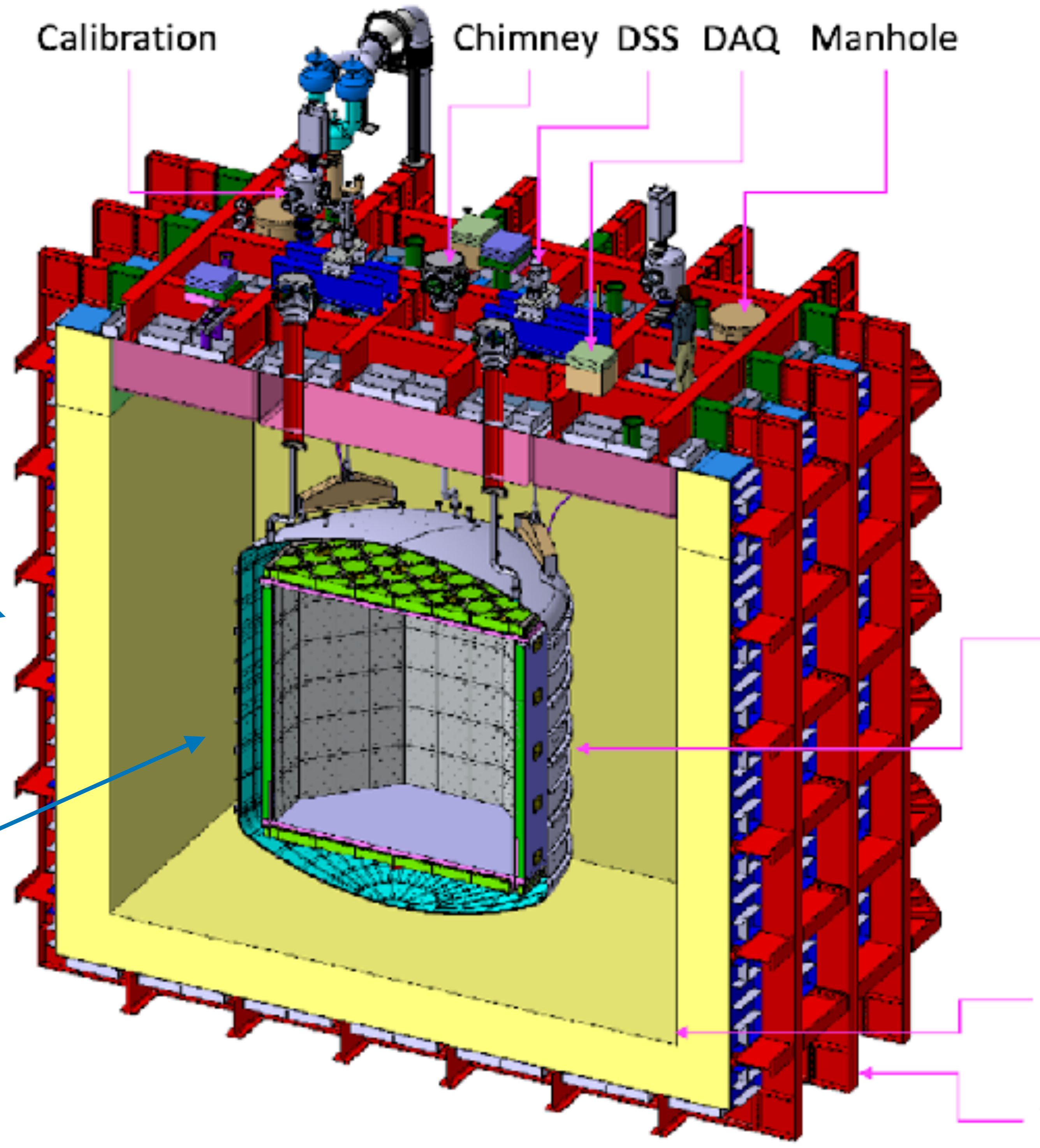


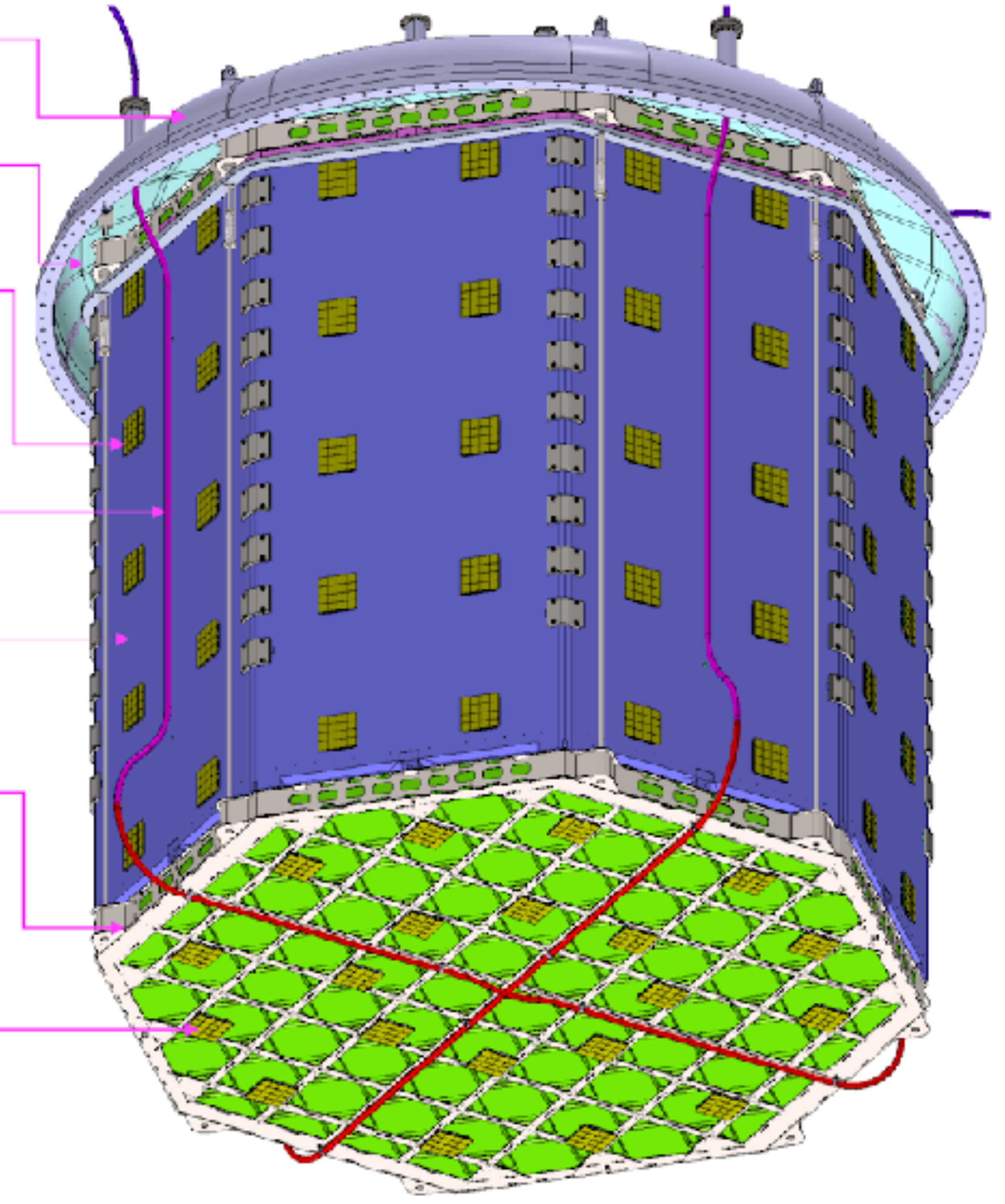


DarkSide-20k @ LNGS

ProtoDUNE-like cryostat (8x8x8m^3)

Ti vessel separating AAr from UAr





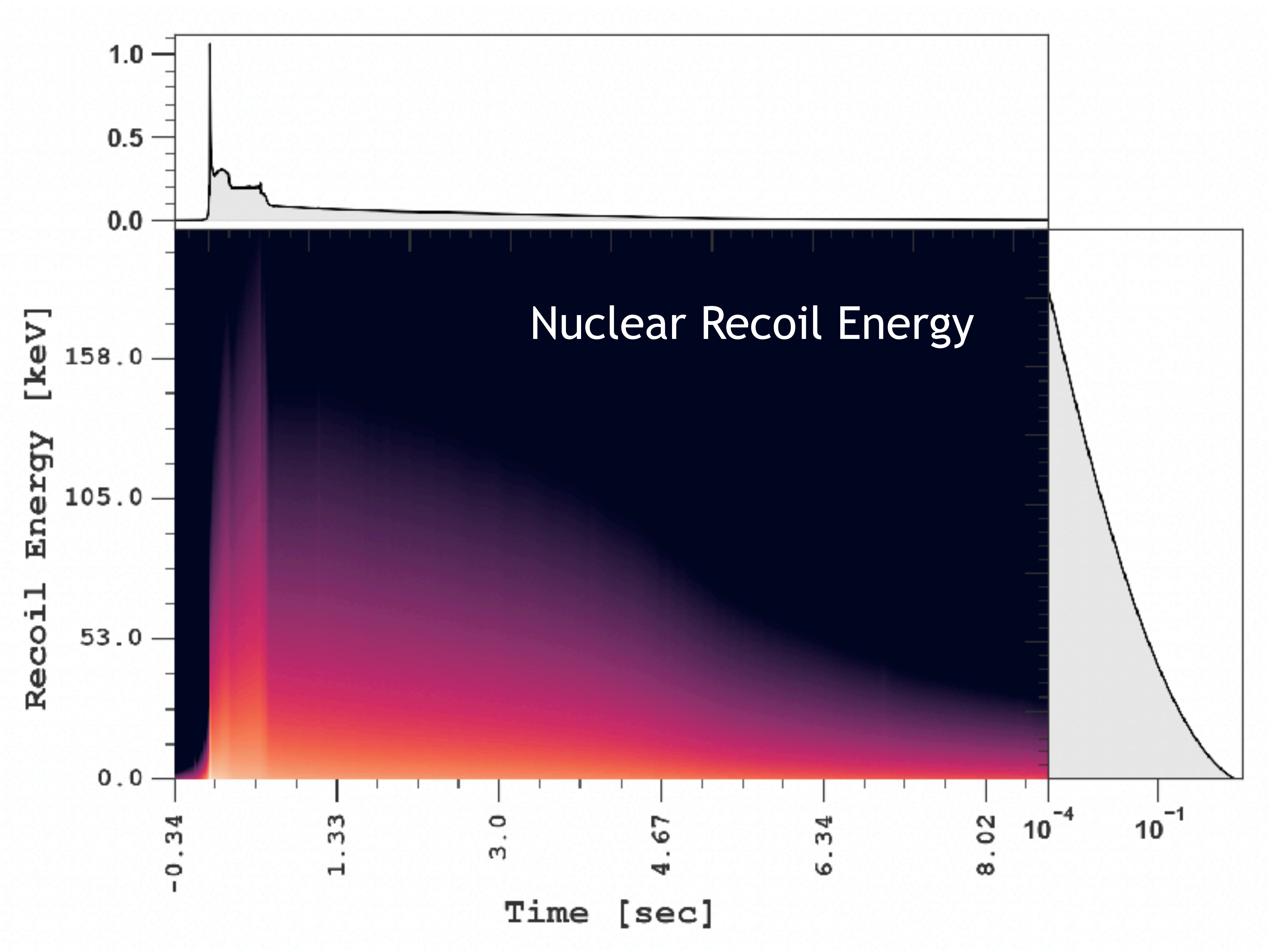
TPC
- 50 ton of underground LAr (dual-phase)
- Gd-loaded acrylic (PMMA) walls
- Walls coated with TPB as WL shifter
- 2112 channels*

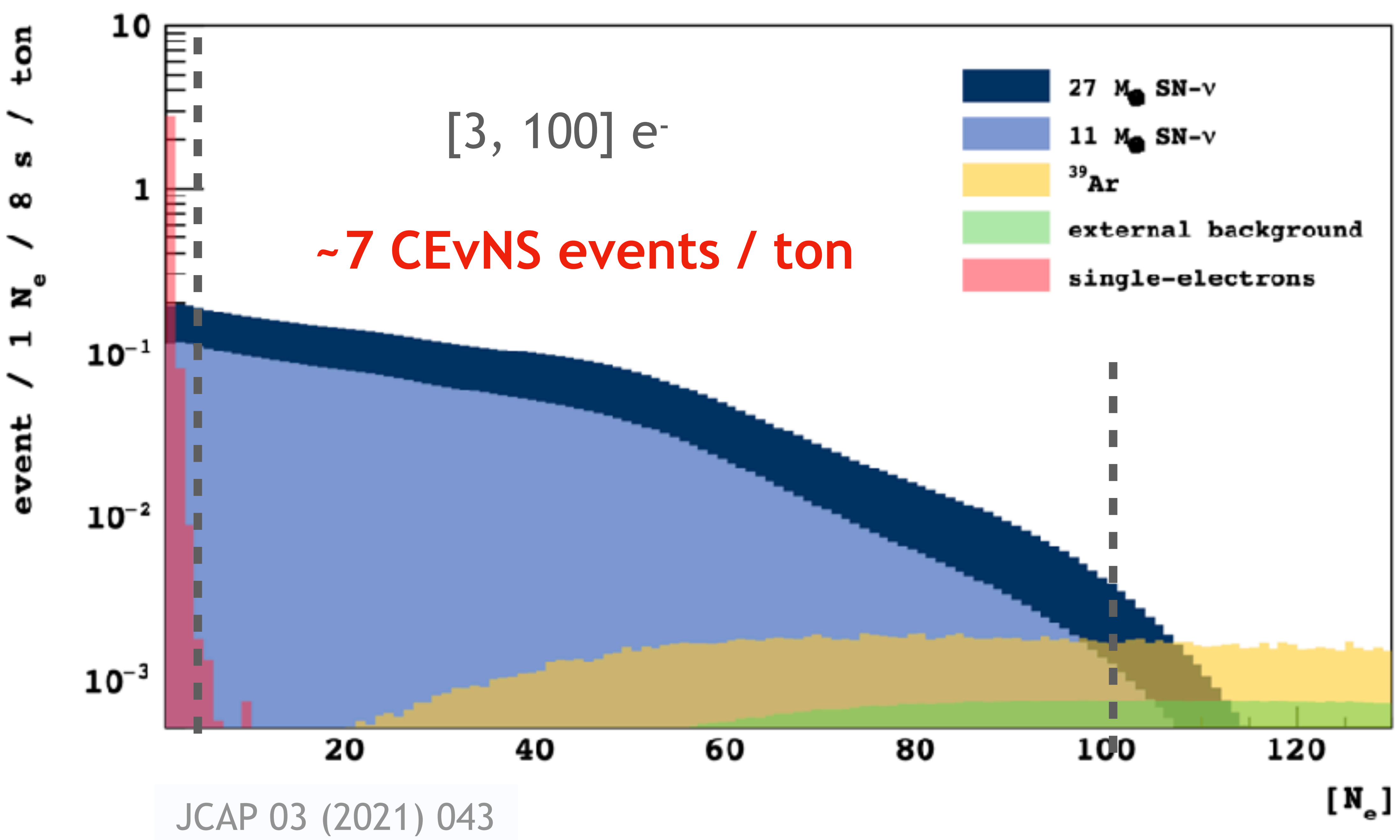
Inner Veto
- 35 ton of underground LAr (single-phase)
- 480 channels*

Outer Veto
- 700 ton of atmospheric LAr (single-phase)
- 128 channels*

(*) each channel = 96 SiPMs

Bollig 2016 / s27.0c model at 10 kpc

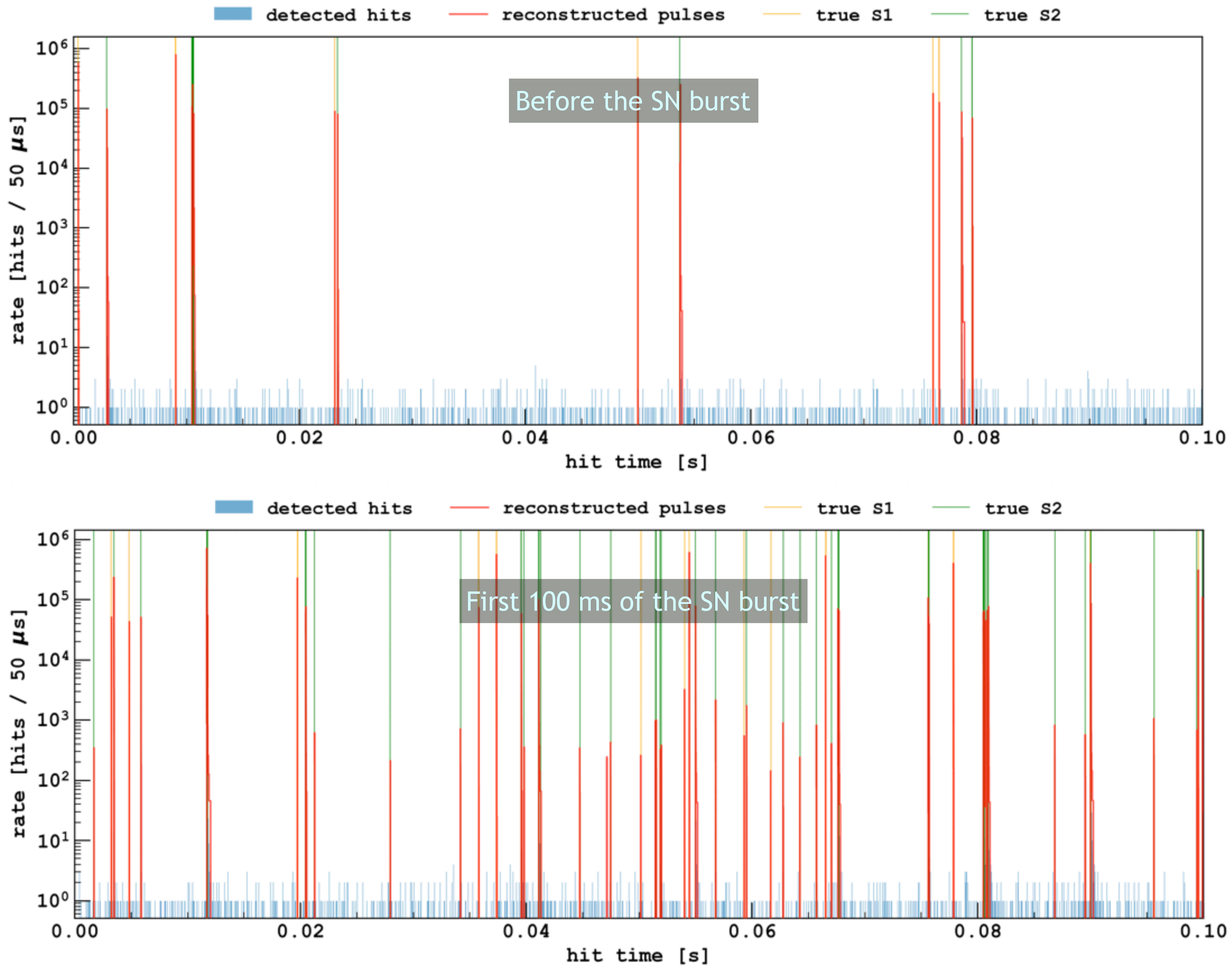




JCAP 03 (2021) 043

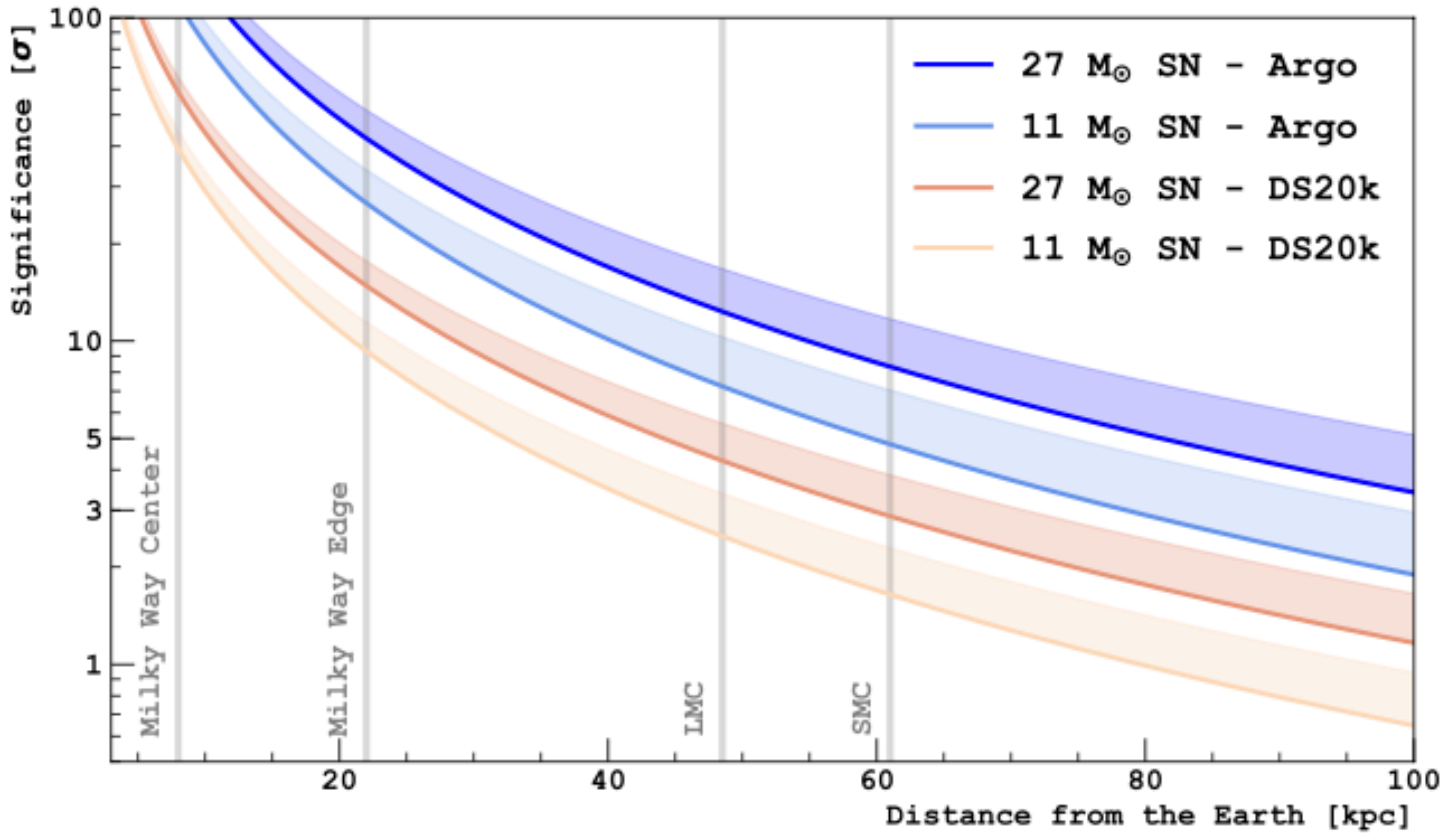
Reconstructed Pulses in DS-20k

- Full radioactive background simulation from most recent screening material campaign
- Waveform simulation with realistic electronic noise
- Simulation of SiPM dark counts, after-pulses, and cross-talks
- Full DAQ emulation
- S1/S2 pulse finder / reconstruction (98% identification efficiency at 1 ionization electron)

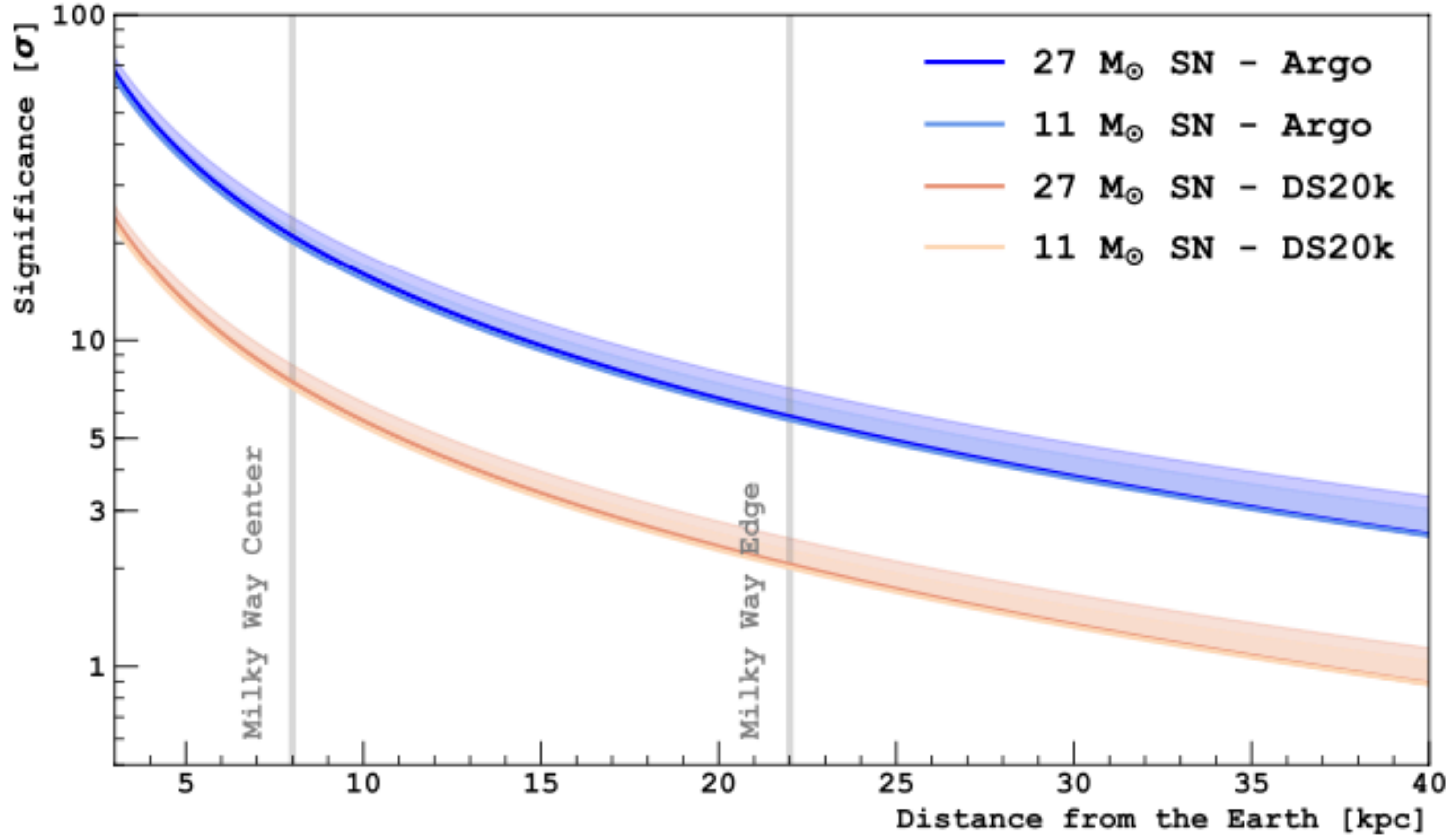


Discovery Sensitivity

Core-collapse SN discovery potential



SN neutronization burst discovery potential



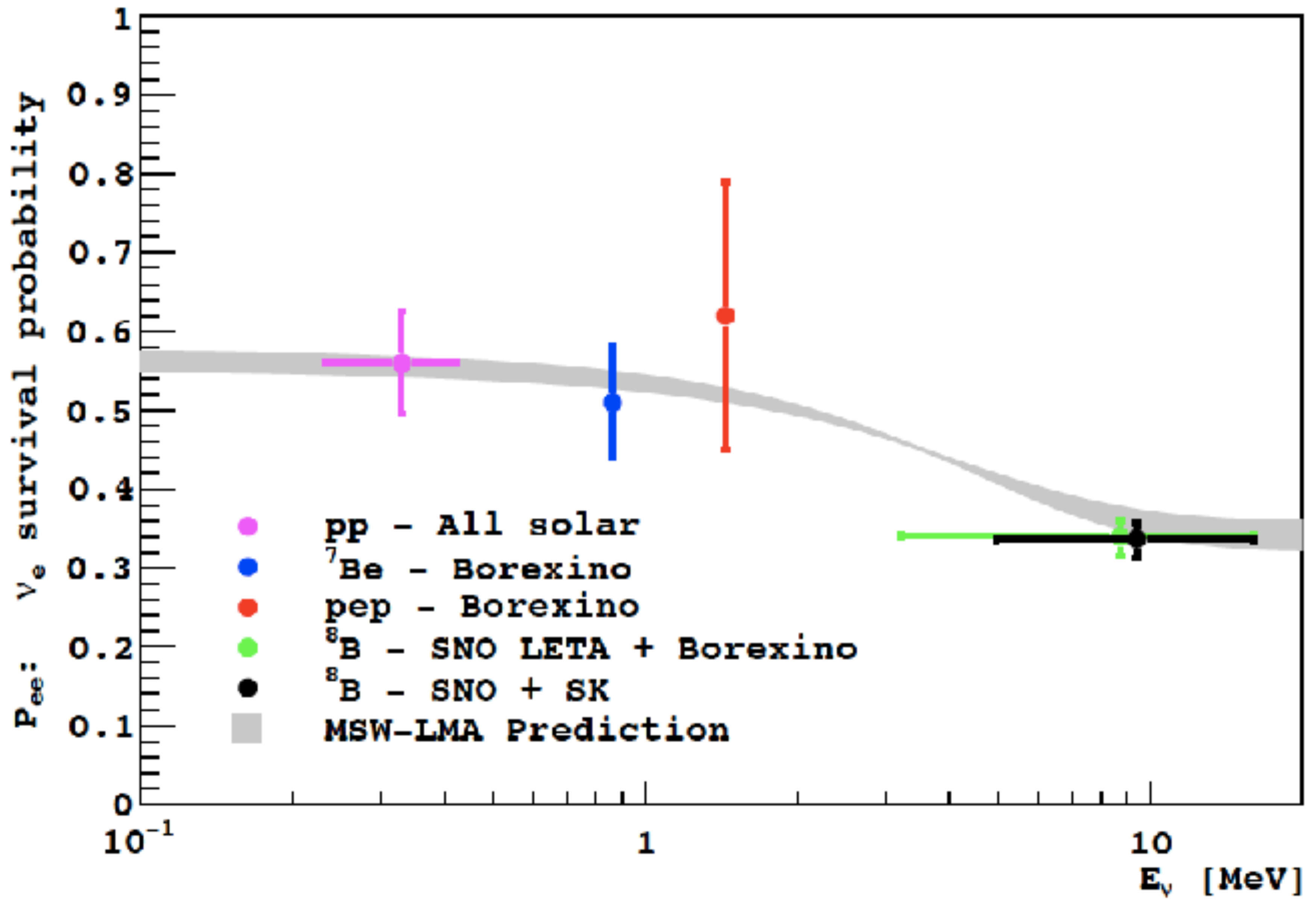
DarkSide Collaboration, JCAP 03 (2021) 043

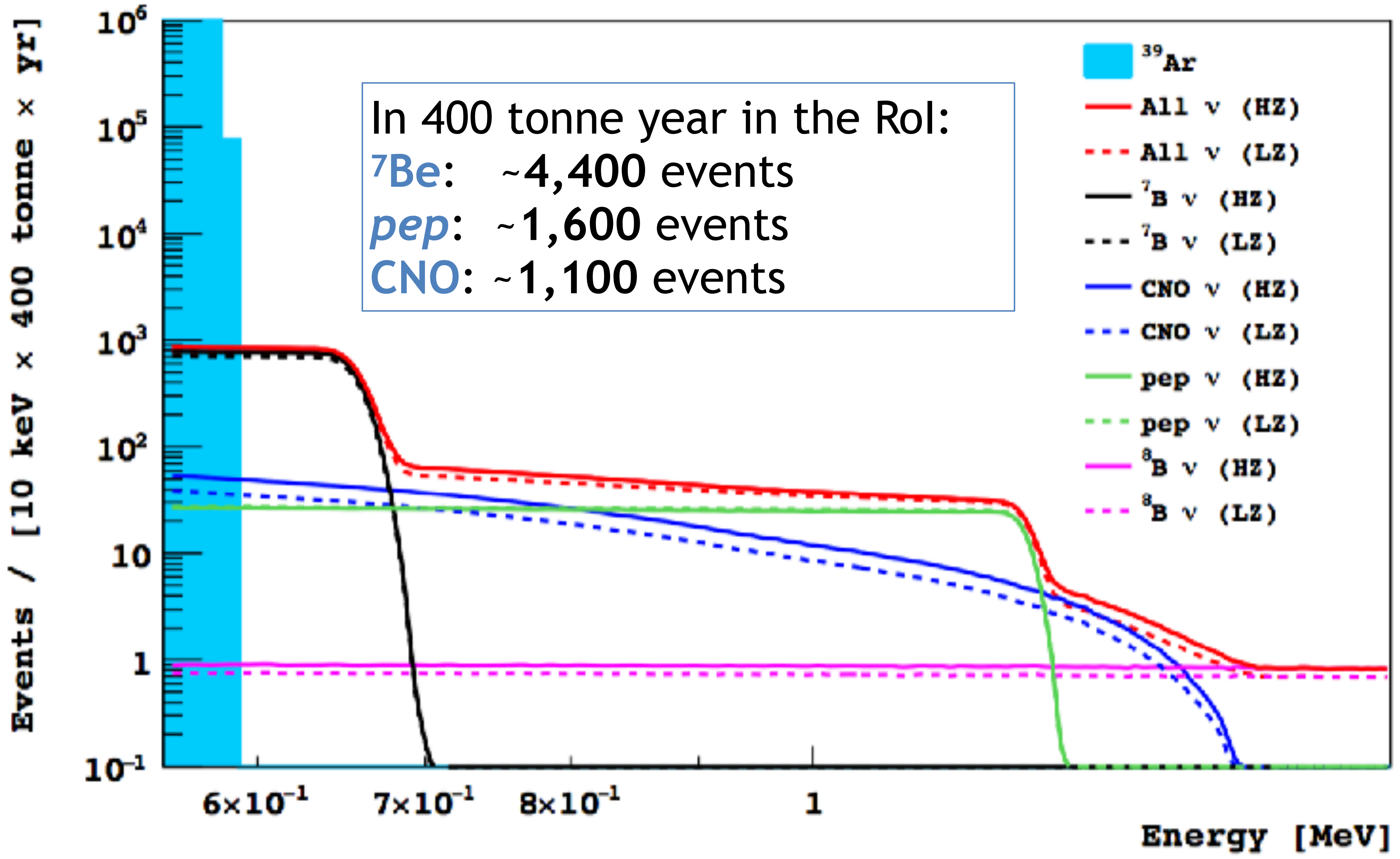
Solar neutrinos via ES with ARGO

ARGO: O(400 ton) UAr

With respect to organic scintillators:
- LY: 500 pe / MeV —> 7000 pe / MeV
- Spatial resolution: 5-10 cm —> 0.2 - 1 cm
- Additional gamma rejection
- Full alpha suppression

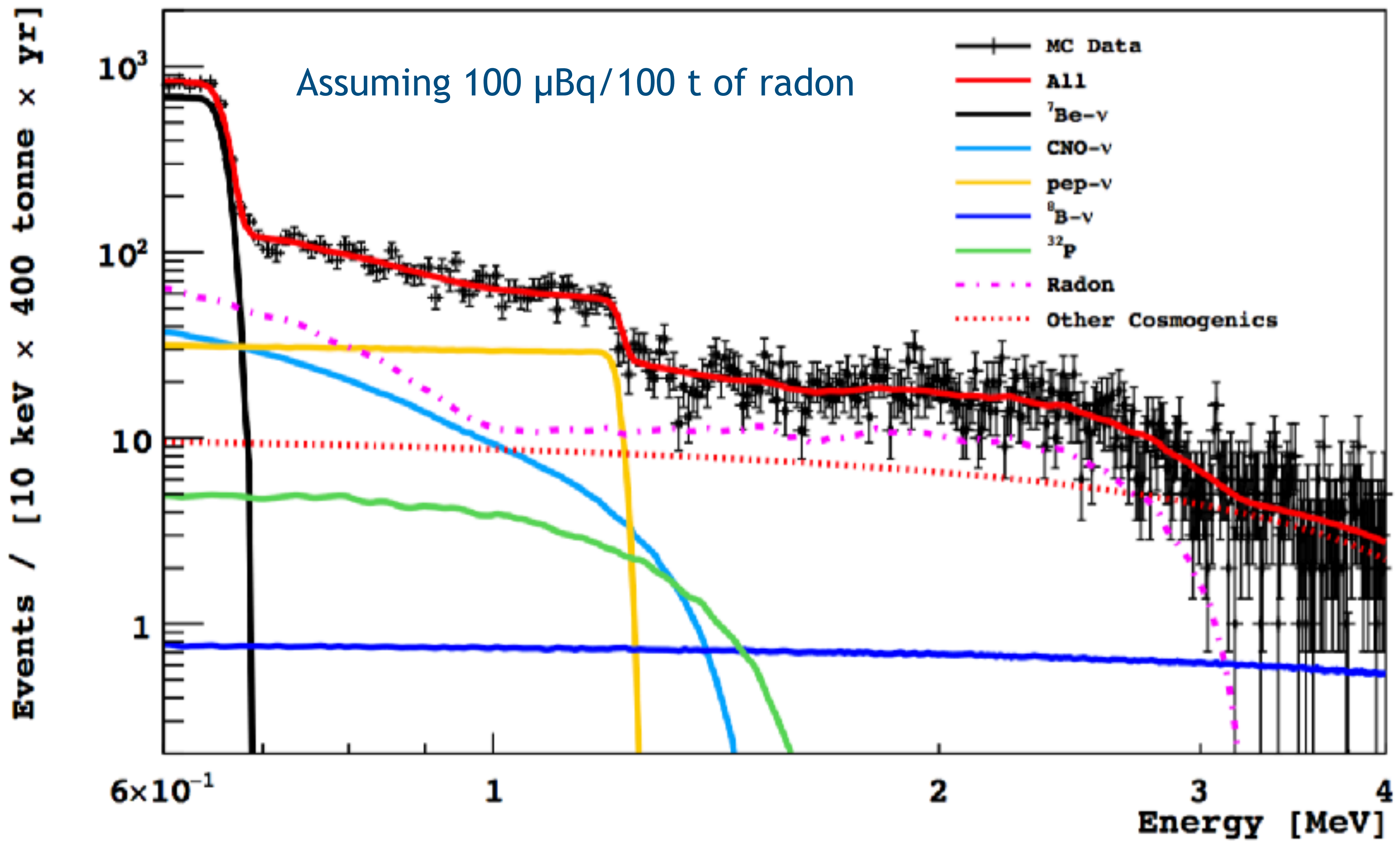
Neutrino Source	Low Metallicity (LZ) All	Low Metallicity (LZ) [0.6-1.3] MeV	High Metallicity (HZ) All	High Metallicity (HZ) [0.6-1.3] MeV
pp	107.9 ± 2.0	0	107.0 ± 2.0	0
pep	2.28 ± 0.05	1.10 ± 0.02	2.23 ± 0.05	1.07 ± 0.02
^{7}Be	36.10 ± 2.60	2.85 ± 0.21	39.58 ± 2.85	3.13 ± 0.23
CNO	3.06 ± 0.30	0.64 ± 0.06	4.28 ± 0.44	0.90 ± 0.09
^{8}B	0.30 ± 0.04	0.035 ± 0.005	0.36 ± 0.06	0.042 ± 0.007
Total	cpd / 100 tonne	4.63 ± 0.22		5.14 ± 0.25

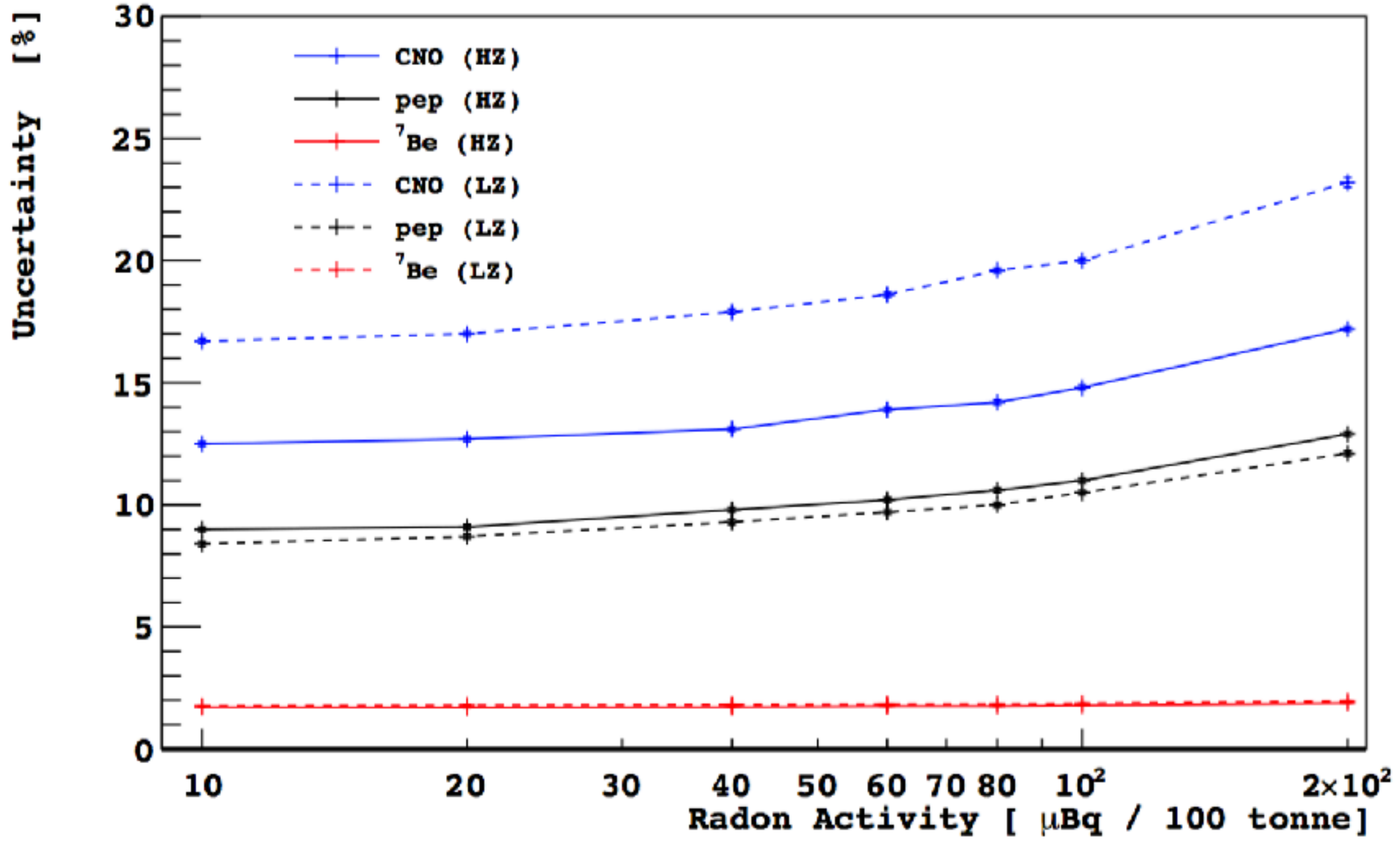




Solar neutrinos via ES with ARGO

Improving Borexino accuracy in 1 year exposure



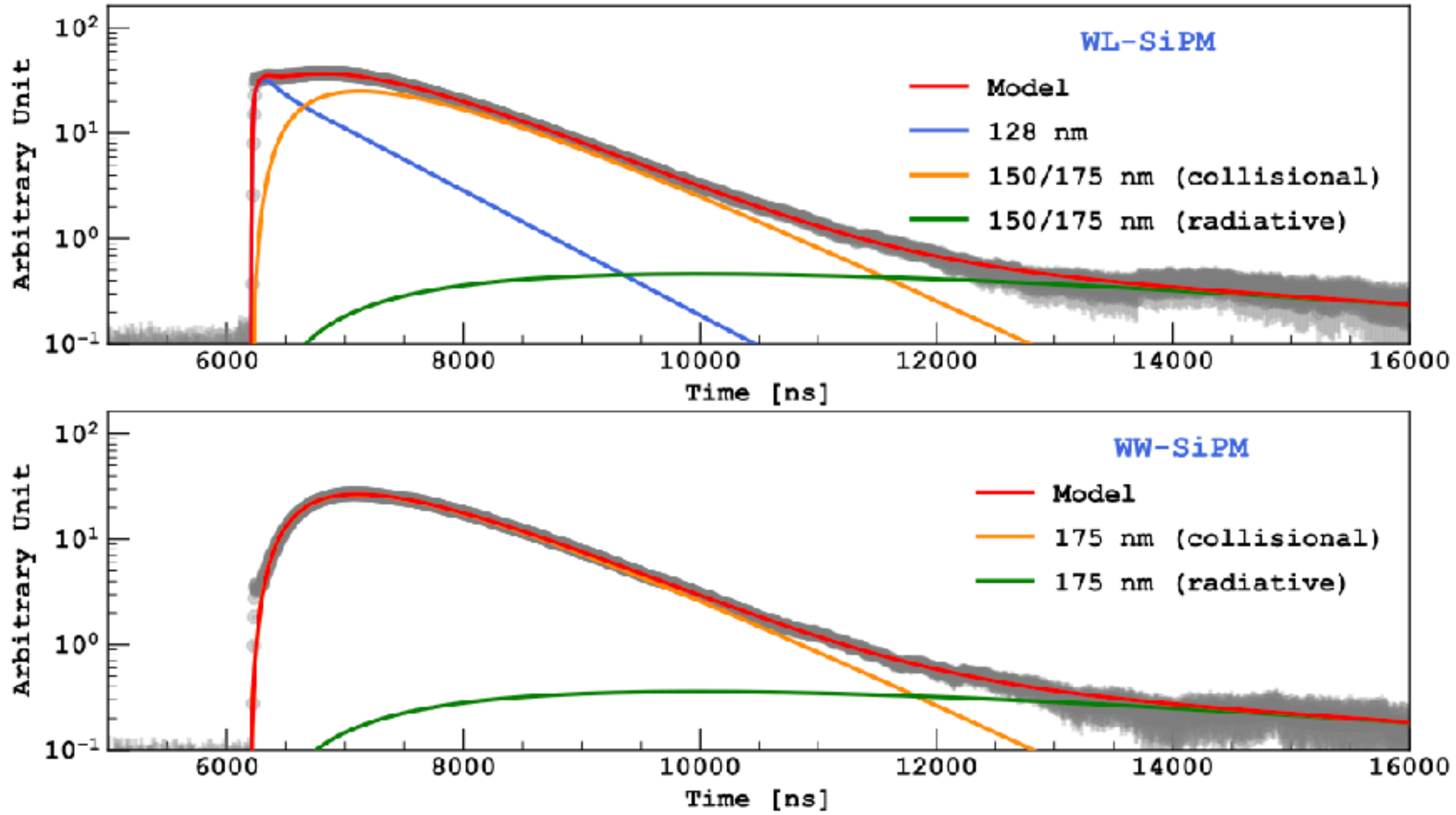


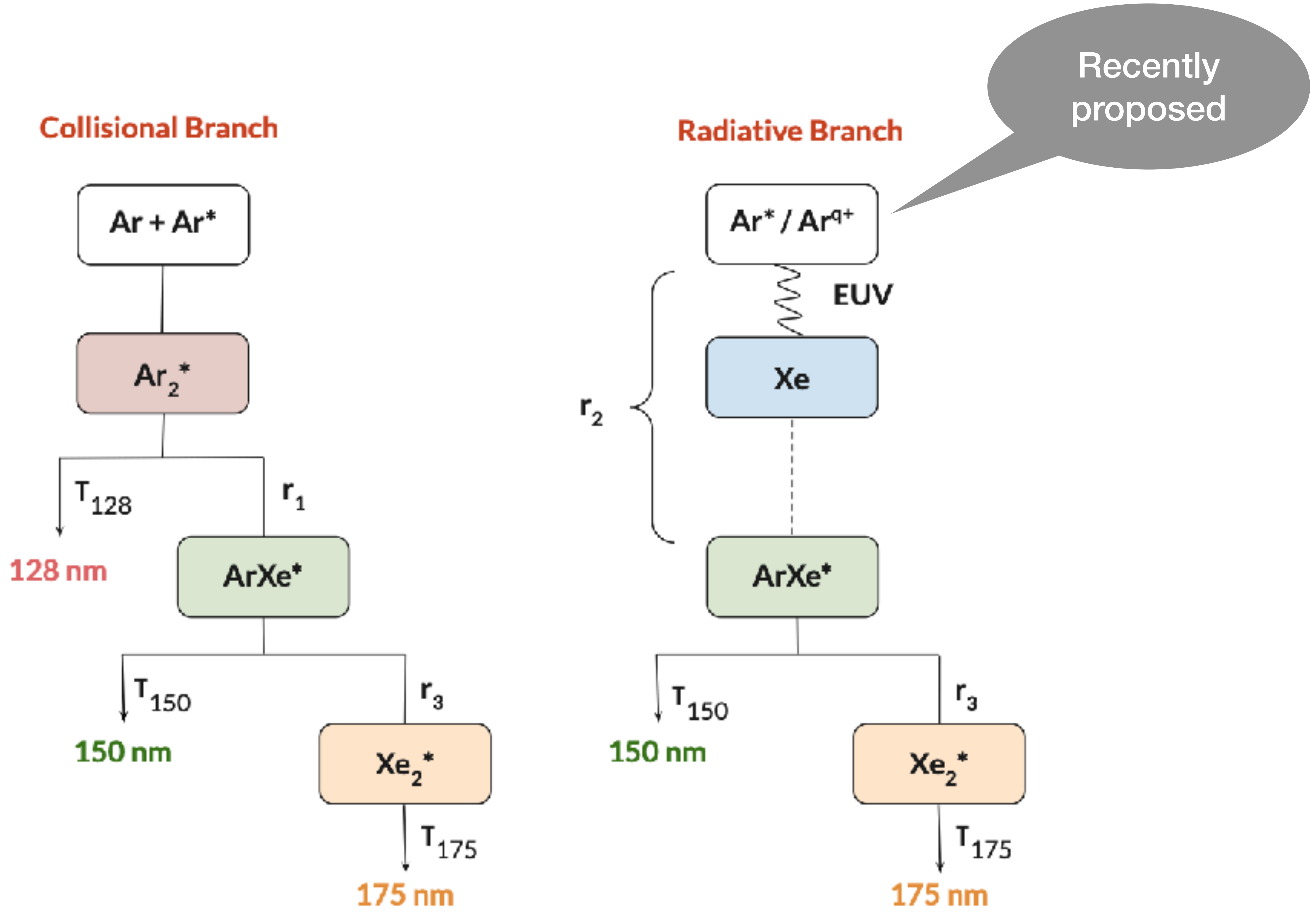
D. Franco et al., JCAP 1608 (2016) 8, 017

How to further improve

Doping LAr with Xenon

- faster scintillation
- higher photon and ionization yields
- longer photon attenuation length
- lower energy thresholds
- argon boiling temperature

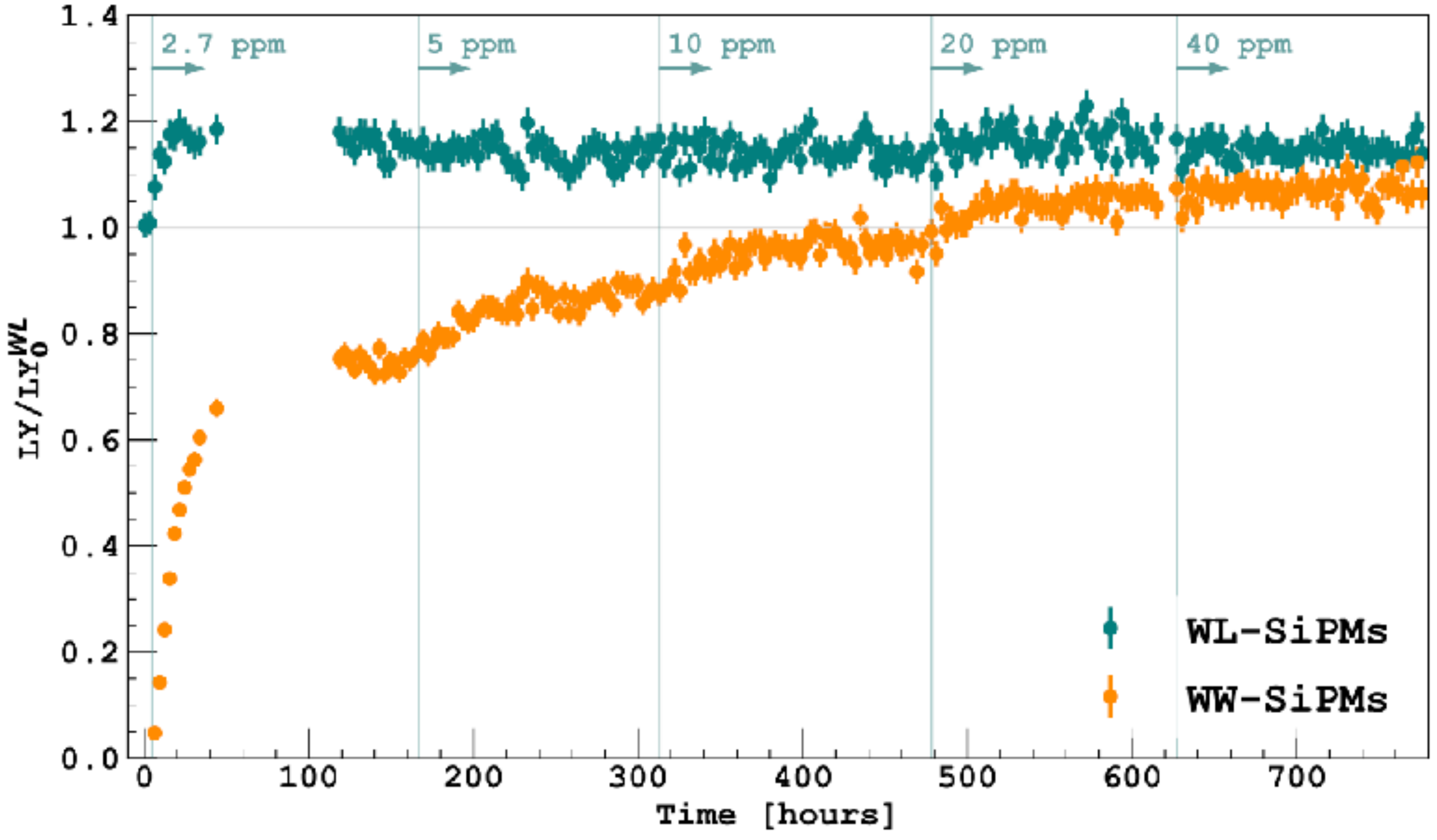




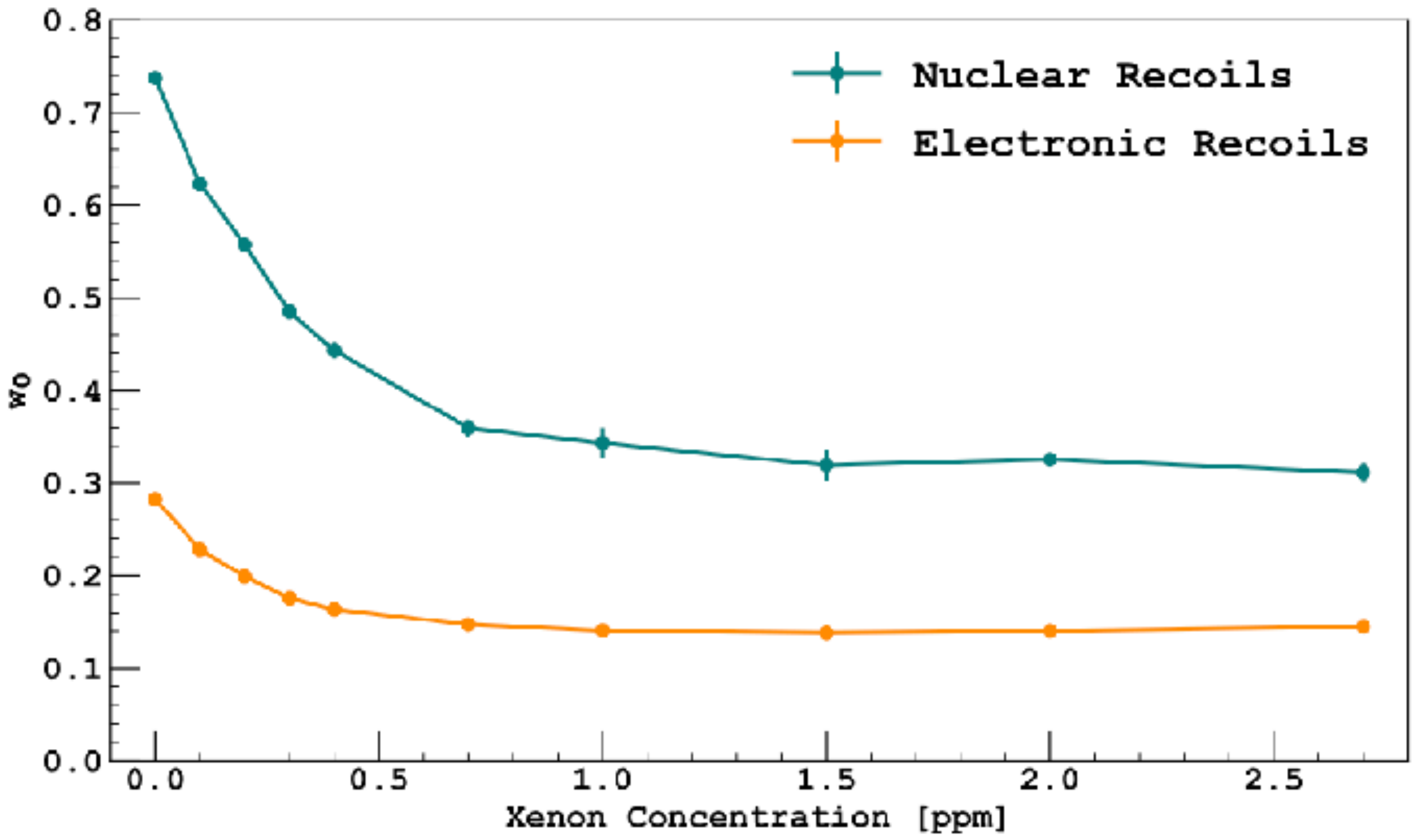
Energy transfer mechanisms for scintillation

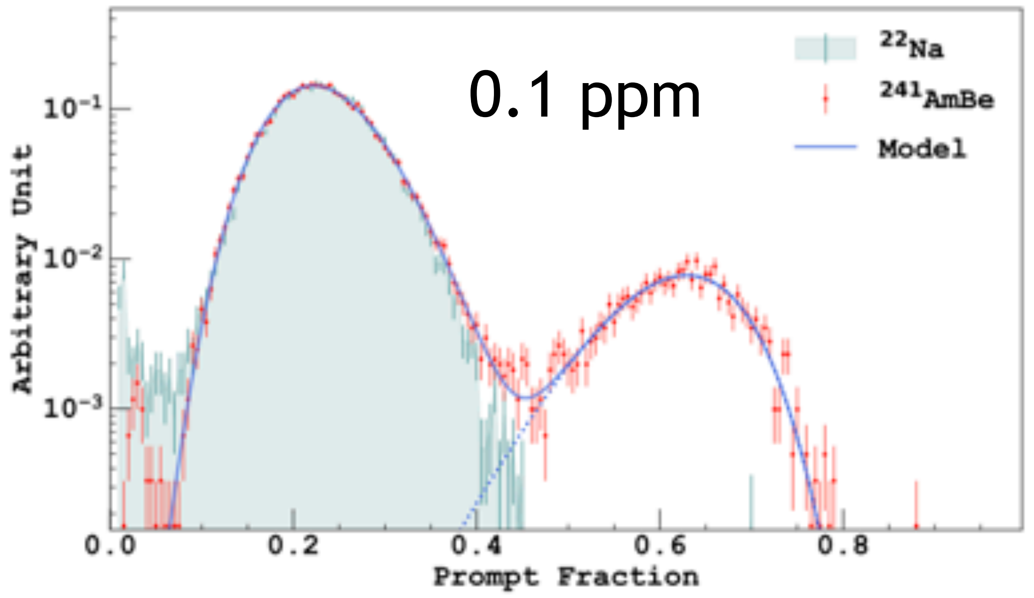
Doping LAr with Xenon

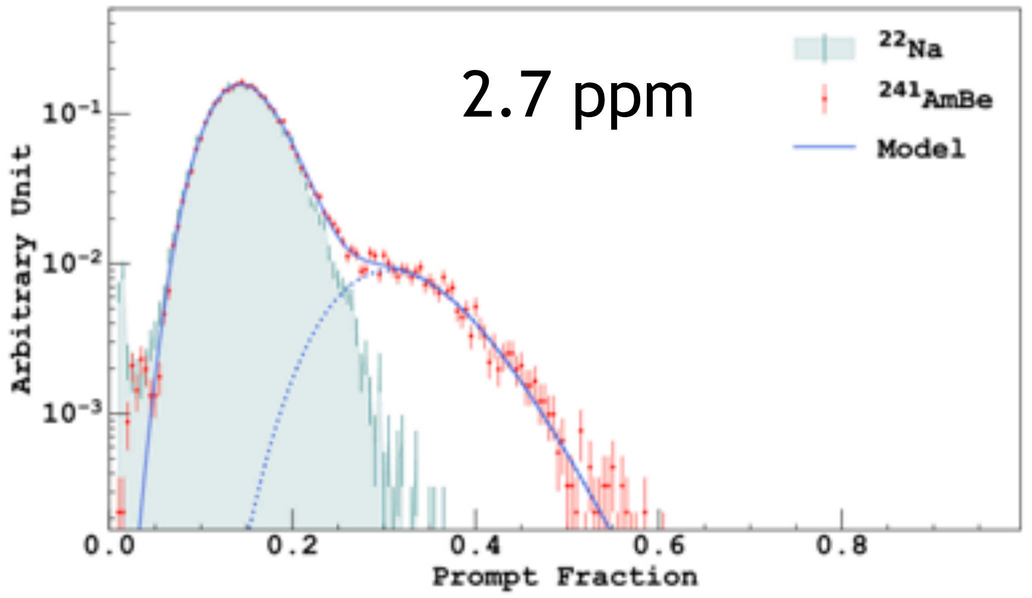
Increasing LY…



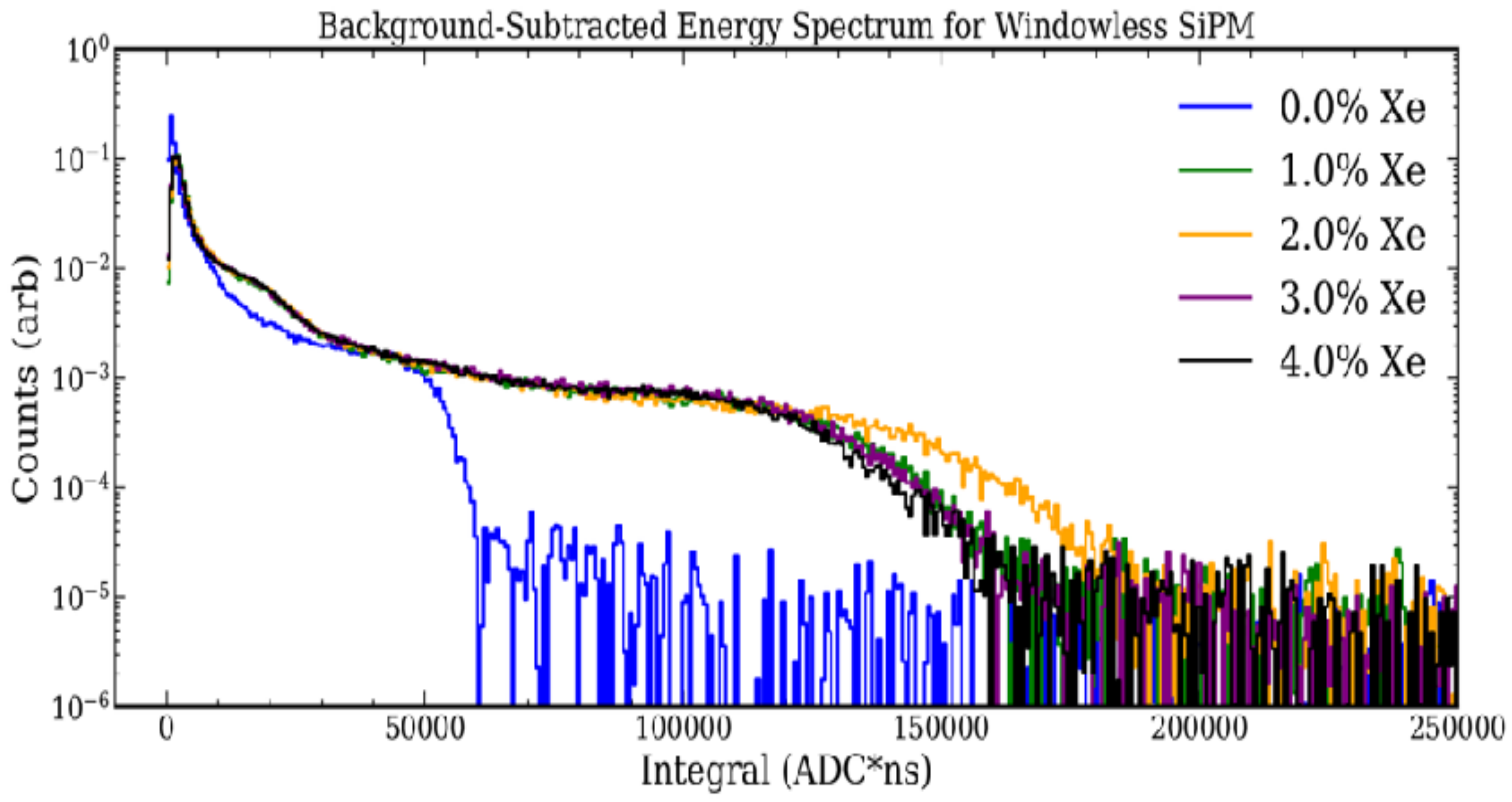
…but decreasing PSD



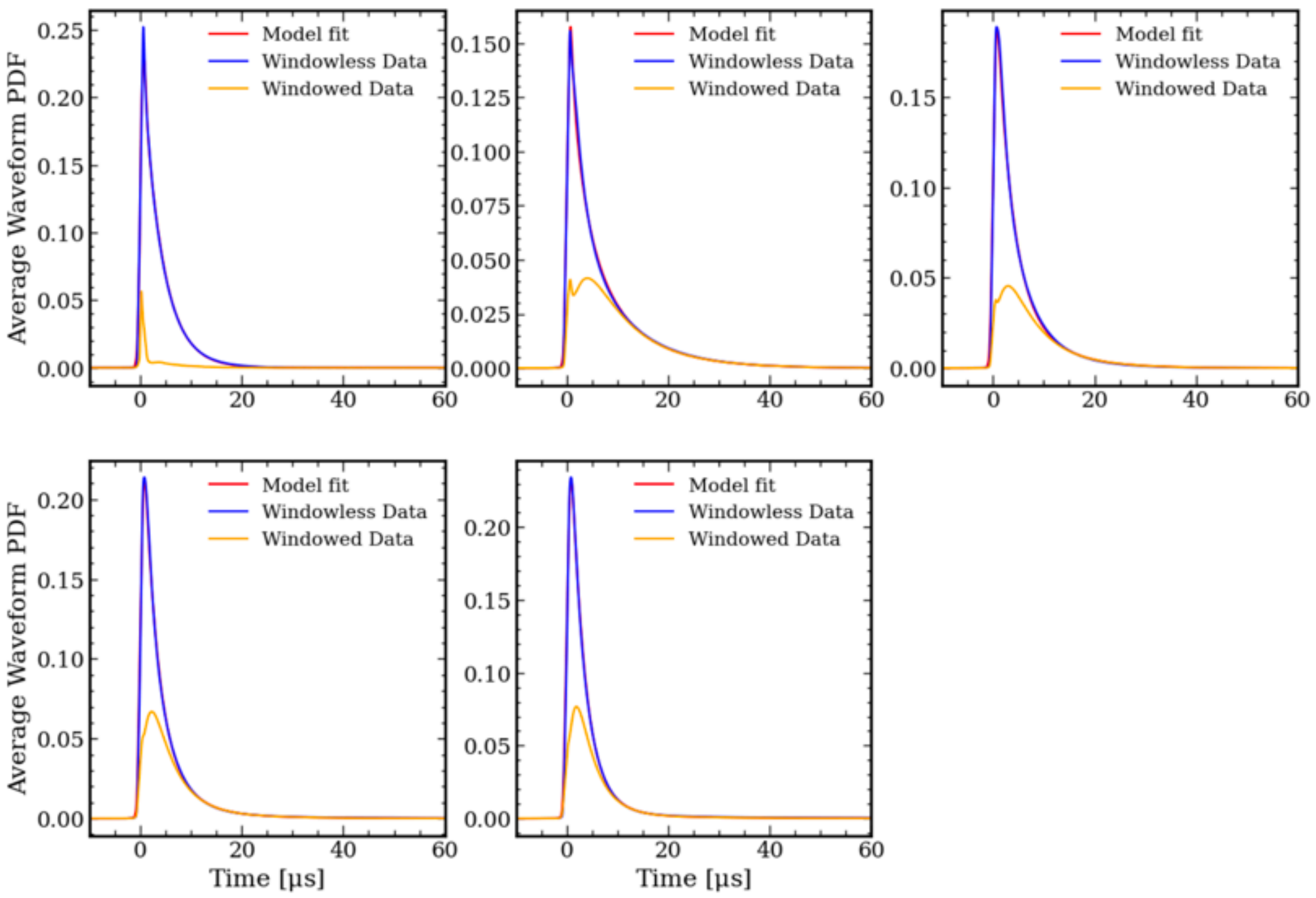




Electroluminescence increased by x2.5



Kingston et al. (https://arxiv.org/pdf/2510.02261)



Conclusions

Toward an O(500-t) scale LAr TPC for low-energy astroparticle physics ?

Light dark matter searches

—> Still providing the world's **best limits** at the GeV mass scale with only 50 kg of target mass

—> Further improvements expected from refined modelling of **spurious electrons** and **quenching fluctuations**

Supernova neutrinos via CEvNS

—> Unique detection channel, **insensitive to flavour**

High-mass WIMP searches

—> Excellent **discovery potential** combining PSD and underground argon purity

Solar neutrinos via ES

—> A unique and complementary **probe of the solar interior**

BACK UP

Reconstructed SN Mean and Total Energies

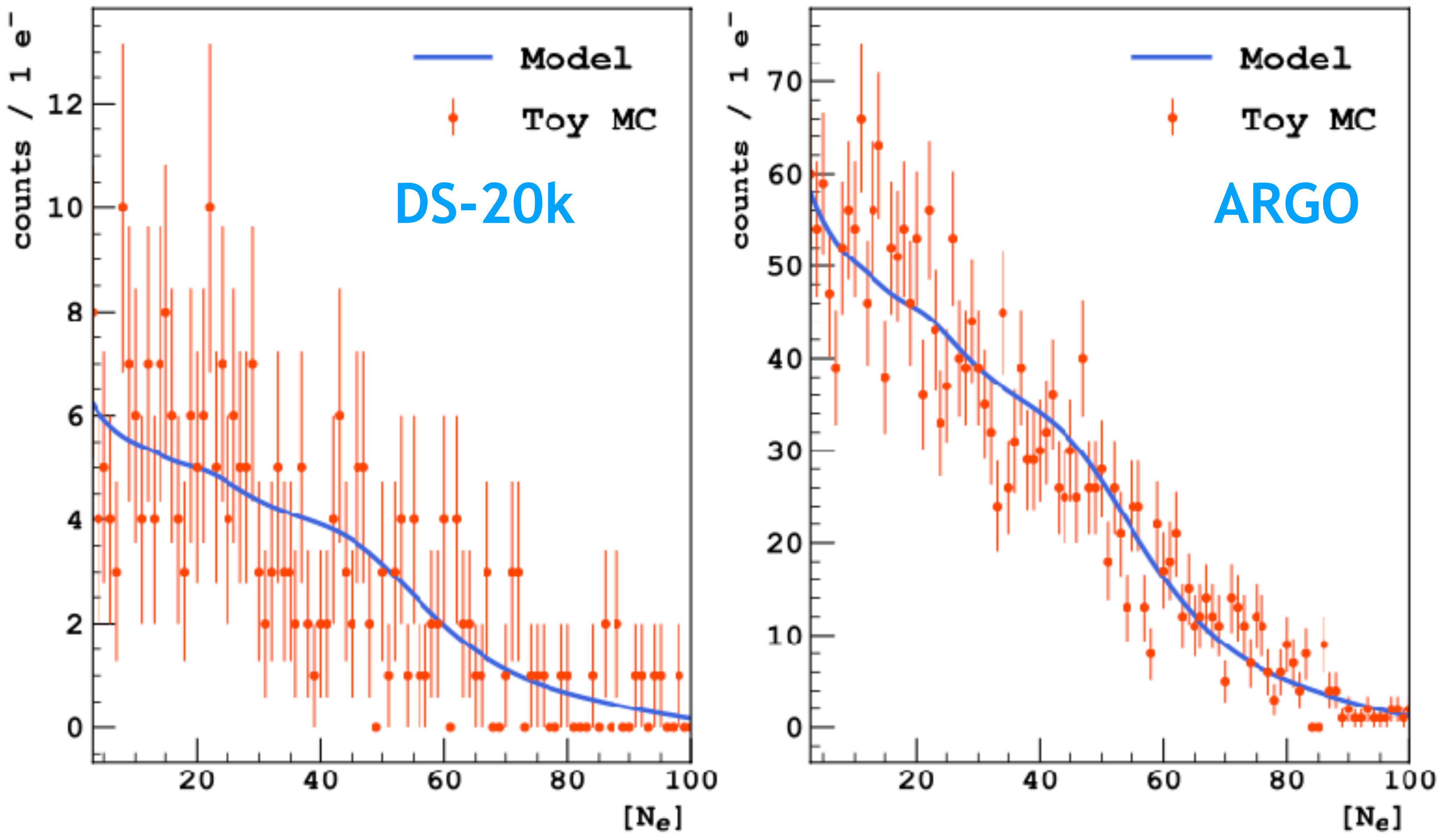
Model = $f(E_\nu) \otimes \mathrm{CE\nu NS}(E_\nu, E_{nr}) \otimes g(E_{nr}, N_e)$

- $f(E_\nu)$: approximated spectrum
- $\mathrm{CE\nu NS}(E_\nu, E_{nr})$: cross section
- $g(E_{nr}, N_e)$: detector response

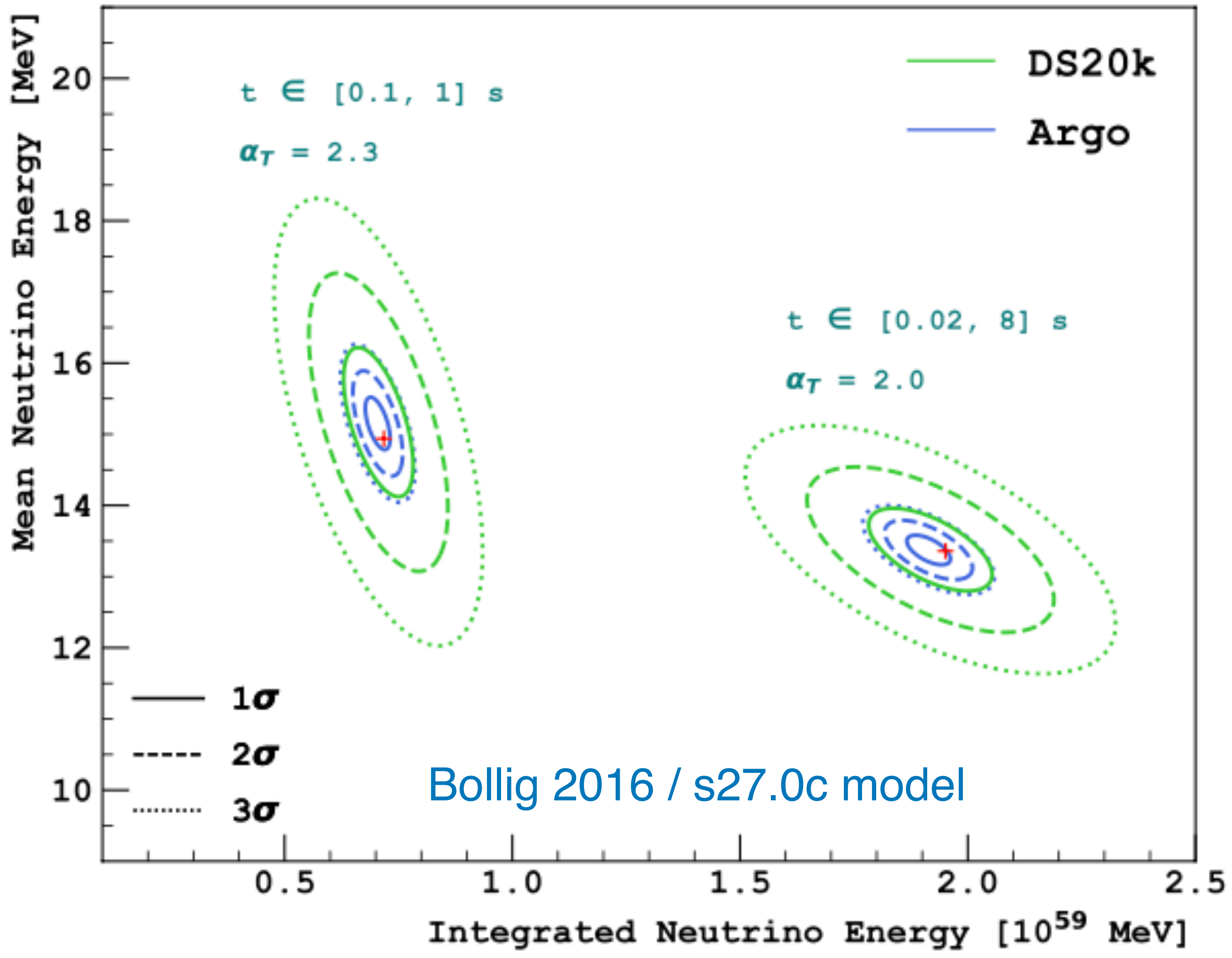
$$f(E_\nu) = \frac{\xi}{4\pi D^2}\,\frac{(\alpha_T+1)^{\alpha_T+1} {E_\nu}^{\alpha_T} e^{-\frac{E_\nu(\alpha_T+1)}{\langle E_\nu\rangle}}}{\langle E_\nu\rangle^{\alpha_T+1}\Gamma(\alpha_T+1)}$$

D = SN distance
ξ = total neutrino energy
$\langle E_\nu \rangle$ = mean neutrino energy
α_T = pinching parameter

M. T. Keil, G. G. Raffelt and H.-T. Janka, Astrophys. J. 590 (2003) 971

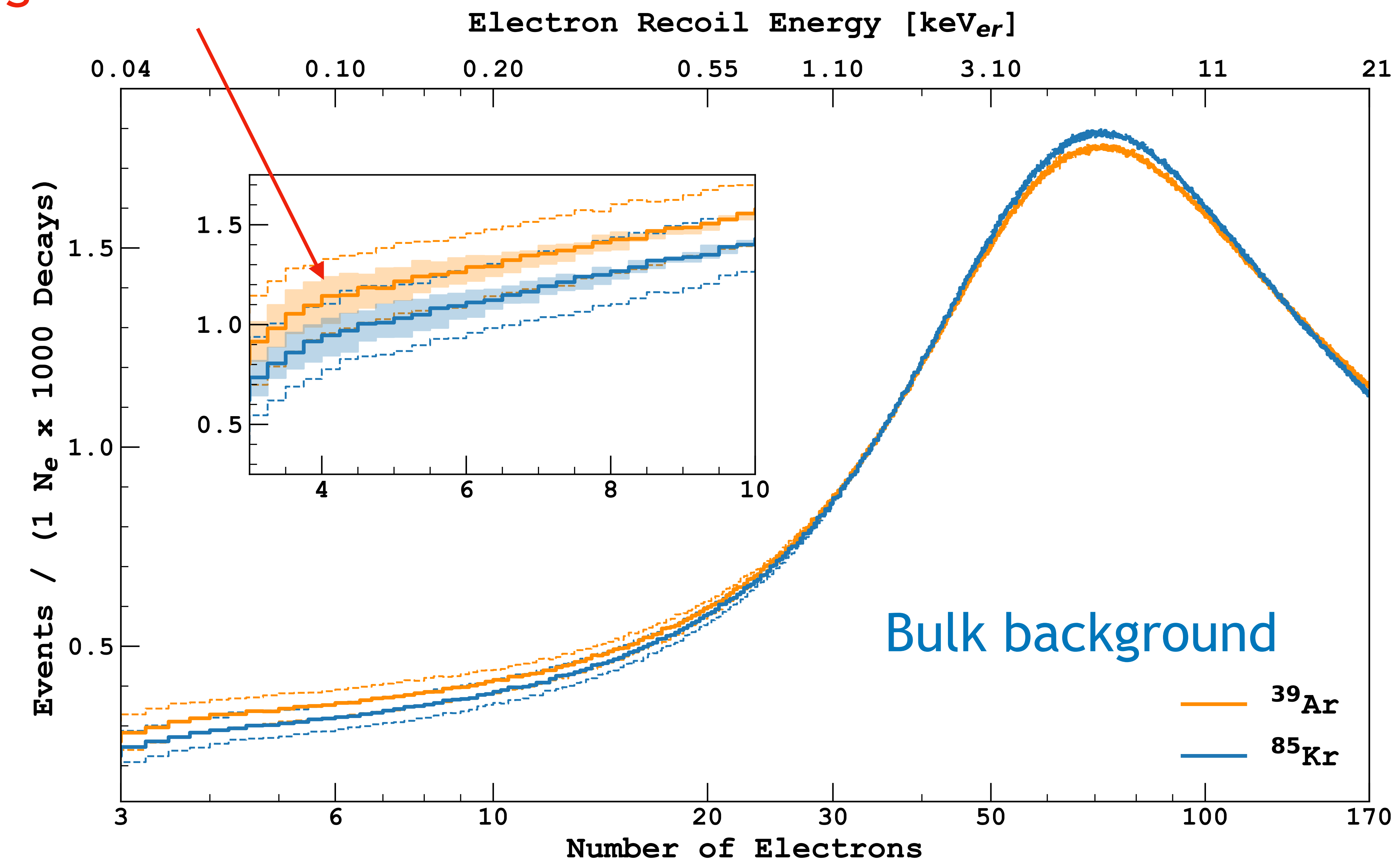


Fitted Toy MC Samples

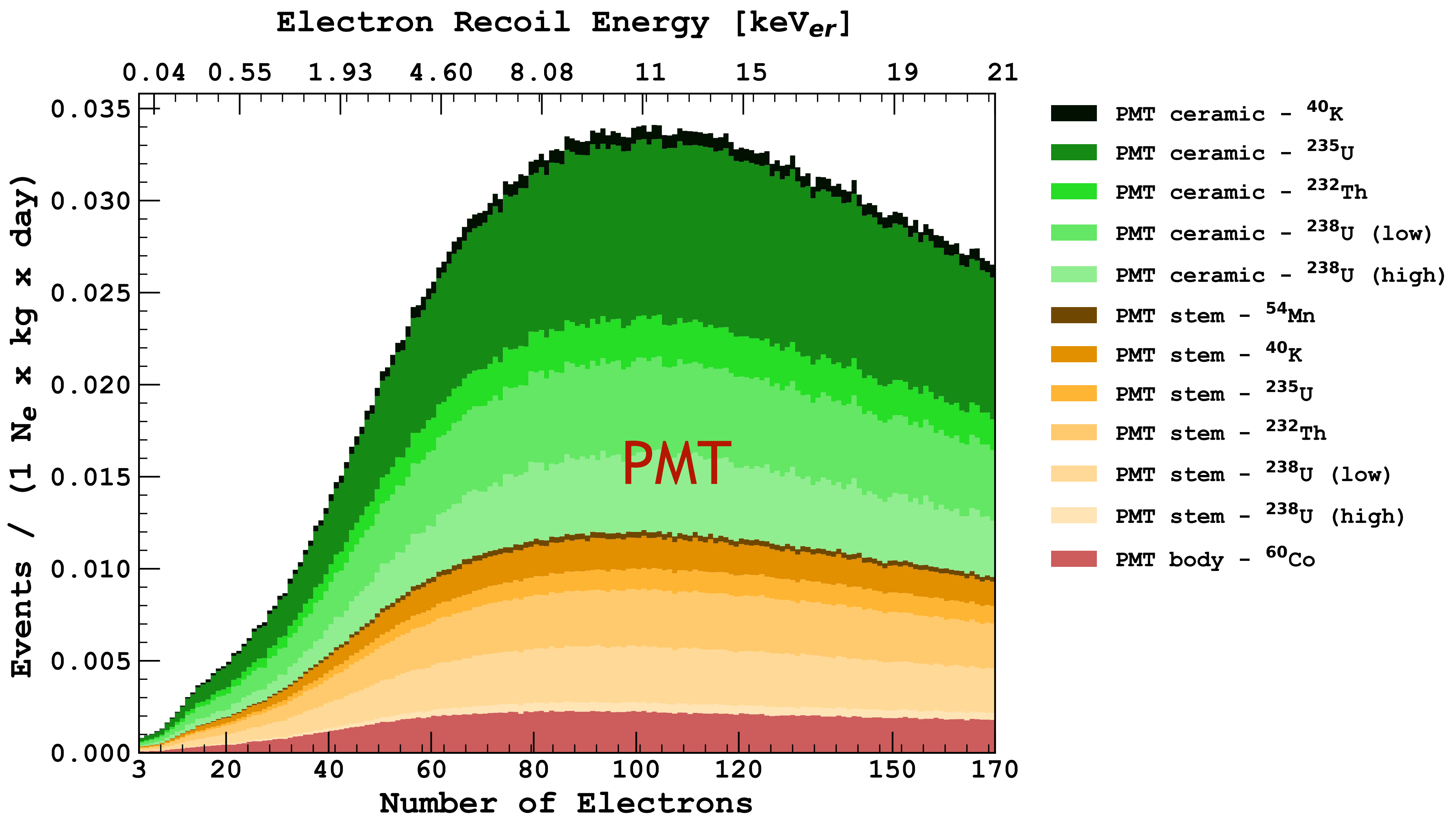


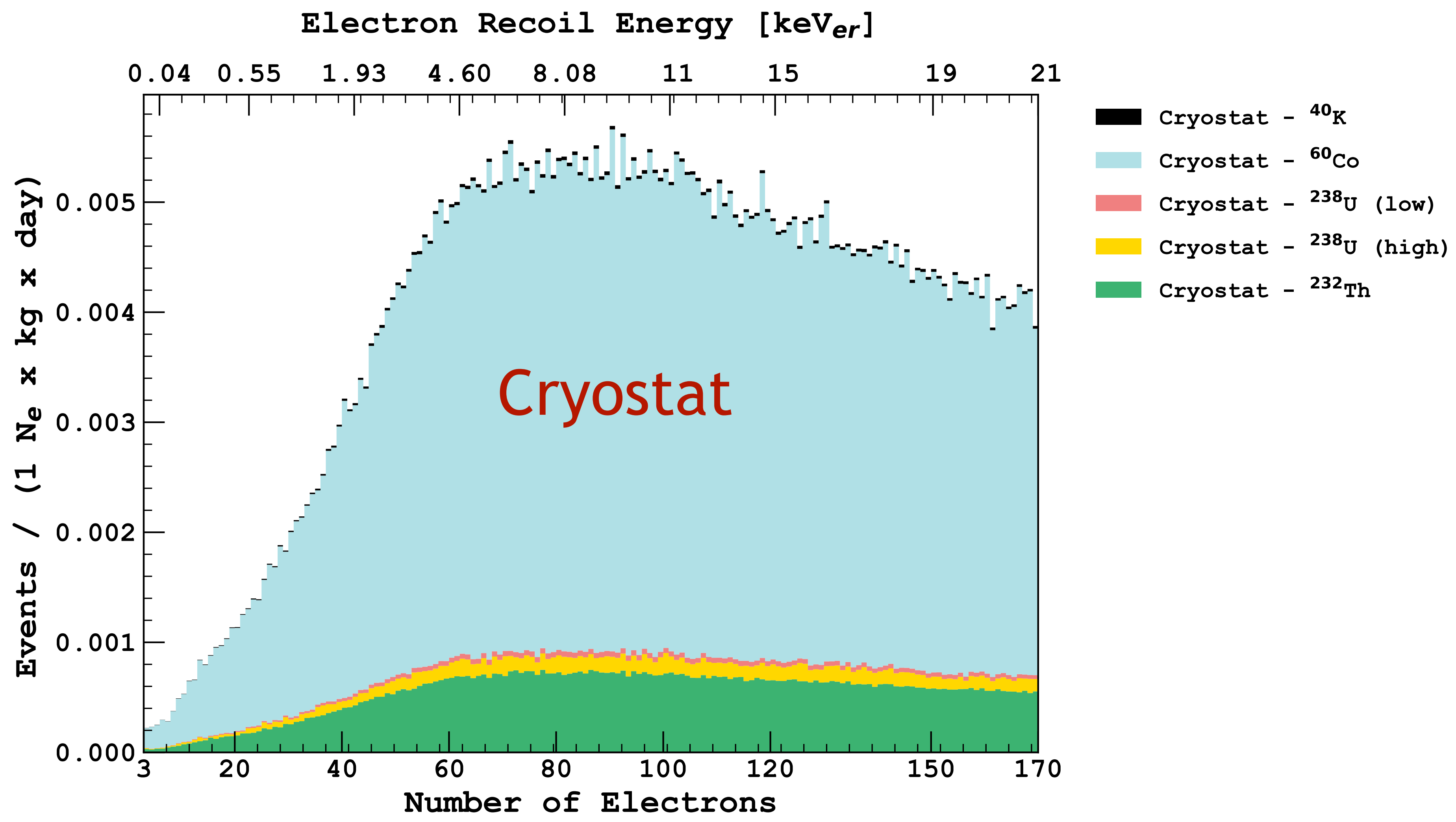
Background Model

Uncertainty from atomic exchange and screening effects



- ^{39}**Ar** activity: **0.7 ± 0.1 mBq/kg**
- ^{85}**Kr** activity: **1.8 ± 0.1 mBq/kg**
- **PMT** and **cryostat** components from material screening measurements





The LAr astroparticle physics programme